The New Datum

Geodetic reference, distortion and continuity in the modernization of the National Spatial Reference System (2022–2026)

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Preliminary Note

This monograph constitutes a stand-alone volume (*one-off*), external to the *No Map Is Best* series and to the Discrete Global Grid Systems project, but methodologically akin to both: it addresses a case of redefinition of the geodetic reference for an entire continent, captured during its active transition phase (2022–2026), with particular attention to the implications for cartographic distortion and for the continuity of historical data.

Epistemic Notice

This volume is a *synchronic* study: a self-contained account of the modernization's architecture, rationale, institutional mechanics, and early reception, deliberately fixed to the evidentiary record available through July 2026, rather than an interim status report meant to be superseded by later editions. The eventual date of the Federal Geodetic Control Subcommittee's approval vote, the exact final wording of any product, and the ultimate resolution of the small number of points this volume explicitly identifies as unconfirmed by primary sources (listed in full in the closing section of the Bibliography) do not alter the analysis offered here of *why* the modernization was designed as it was and *how* it unfolded up to this point — which is the volume's actual subject. All quantitative data reported are drawn from primary NGS technical documents (Blueprint Documents, Federal Register Notices, official FAQs) and the further primary and quasi-primary sources listed in the Bibliography, each with its consultation date. Where a specific figure or claim could not be corroborated from a primary source as of that date, this is stated explicitly in place, as a permanent feature of the record this volume constitutes — not as an invitation to the reader to seek a more current answer elsewhere.

This volume does not report new geodetic measurements, and makes no claim to. Its contribution lies elsewhere: in the formal treatment applied throughout to a case that primary NGS sources describe administratively but do not themselves formalize — the Euler-pole rotation between reference frames (chapter 3), the propagation of covariance through the fourteen-parameter time-dependent Helmert transformation (chapter 14), and the strain-rate decomposition underlying the intra-frame velocity model (chapter 17), each worked through explicitly and tied back to the primary-source figures from which it starts. The value of the volume is this connective and formal work, together with the discipline — documented source by source in the Bibliography — of separating what is confirmed by primary NGS documentation from what rests only on secondary or trade-press reporting. A reader looking for newly measured geodetic data will not find it here; a reader looking for a single, formally worked, source-disciplined account of why the modernized NSRS was designed as it was will.

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Part I

The Geodetic Problem

Chapter 1

Why Change a Datum

1.1 The two datums in force

Since 1986 (NAD 83) and 1991 (NAVD 88), the position of every geographic point in the United States — and therefore every map, every cadastre, every georeferenced piece of infrastructure — has rested on two distinct reference systems: a horizontal one (latitude, longitude) and a vertical one (orthometric height). The North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88) have formed the invisible backbone of North American cartography for four decades.

Both present structural limitations, not simply "aging":

- **NAD 83** is not geocentric: the origin of the reference ellipsoid is offset by roughly 2.2 meters from the Earth's actual center of mass, a legacy of the positioning technology available in the 1980s, prior to the full maturation of GNSS.

- **NAVD 88** was built on geometric leveling — a differential method, extremely accurate over short distances (sub-millimeter over one kilometer) but subject to error accumulation at continental scale — and anchored to a single fixed point, Father Point, in Rimouski, Quebec. The entire North American vertical network descends from that single choice.

1.2 How the problem was discovered

The quantitative discovery of NAVD 88's limitations was not immediate. It was made possible only by the combination of two technologies that matured in the first half of the 2000s: centimeter-accurate GNSS ellipsoidal heights, and continental-scale geoid models derived from the GRACE satellite mission, accurate to the centimeter at wavelengths longer than about 200 kilometers. Only then was it possible to apply the fundamental equation of physical geodesy,

$$H \approx h - N,$$

where H is the orthometric height, h the GNSS ellipsoidal height, and N the geoid undulation, and to systematically compare NAVD 88 values with those derived independently from satellite and GNSS data. The comparison revealed a systematic discrepancy (NGS Blueprint Part 2, ch. 6): NAVD 88 turns out to be biased, on average, by 50 centimeters across the contiguous United States (CONUS) and tilted by roughly one meter along the line running from the Pacific Northwest to southern Florida (see Chapter 9 for the full quantitative analysis).

Key Result

The fundamental equation $H \approx h - N$ is not merely a definition: it is also, read as an error-propagation relation, the reason a geoid model's own accuracy directly limits orthometric-height accuracy however good GNSS becomes. If h and N carry independent uncertainties σ_h, σ_N, standard first-order error propagation gives

$$\sigma_H = \sqrt{\sigma_h^2 + \sigma_N^2},$$

the same quadrature relation used later, with epoch-dependent subscripts, for $\sigma_{H_{\mathrm{NAPGD2022}}}$ in Chapter 7. Because centimeter-accurate GNSS drove σ_h down first, the geoid term σ_N became, by the 2000s, the dominant contributor to σ_H — which is exactly the quantitative precondition that made the systematic NAVD 88 comparison described below possible in the first place: only once $\sigma_N \lesssim \sigma_H^{\mathrm{NAVD88}}$ could a geoid-based height be trusted enough to reveal NAVD 88's own errors, rather than the reverse.

Key Result

The cost/benefit estimate for a complete re-leveling of the NAVD 88 network, calculated by NGS in preparation for the 2008–2018 Ten-Year Plan, came out between 200 million and 2 billion US dollars — and would in any case have been insufficient to resolve the three structural problems: the systematic accumulation of error at continental scale, the possibility that benchmarks move without being detected, and their vulnerability to physical destruction.

1.3 The choice of a new paradigm

Faced with these structural limitations — not correctable through incremental adjustment — NGS opted, as early as the 2008–2018 Ten-Year Plan, for a paradigm shift rather than an update of the existing system: replacing the entire National Spatial Reference System (NSRS) with a system founded on:

1. four new, tectonically distinct *terrestrial reference frames*, rather than a single rigid datum (Chapter 2);
2. a gravimetric vertical datum, dynamic in time, rather than a static leveling network (Chapters 6 and 7);
3. primary access via the GNSS/CORS network, rather than through direct occupation of physical benchmarks (Chapter 15).

The common name chosen for this set of components — North American Terrestrial Reference Frame of 2022 (NATRF2022) and North American–Pacific Geopotential Datum of 2022 (NAPGD2022) — reflects the year the project was originally meant to conclude. As will be seen in Chapter 24, the actual timeline proved considerably longer.

Chapter 2

From a Single Datum to Four Tectonic Reference Frames

2.1 The multiple-plate problem

NAD 83 treated the whole of North America as a single rigid block. This simplification was reasonable in 1986: the instrumentation of the time could not resolve the differential rotations of individual tectonic plates with the accuracy needed to make them operationally relevant. The availability of decades of continuous GNSS observations, via the CORS (Continuously Operating Reference Stations) network, has instead made measurable — and no longer negligible — the fact that the territory covered by the NSRS does not rest on a single plate, but spans at least four tectonic systems with appreciable relative motion: the North American plate proper, the Pacific plate, the Caribbean plate, and the Mariana plate.

Key Result

The modernized system replaces the single North American Datum of 1983 with four distinct, mutually consistent reference frames, each tied to its own plate:

- ***NATRF2022*** *— North American Terrestrial Reference Frame of 2022 (North American plate; covers CONUS, most of Canada, continental Alaska);*
- ***PATRF2022*** *— Pacific Terrestrial Reference Frame of 2022;*
- ***CATRF2022*** *— Caribbean Terrestrial Reference Frame of 2022;*
- ***MATRF2022*** *— Mariana Terrestrial Reference Frame of 2022.*

2.2 Implications for the non-specialist user

A crucial point, often misunderstood in popular communication on the topic, is that the four reference frames do not introduce four mutually incompatible coordinate systems with arbitrary differences: the differences among the four frames are, by construction, limited to small horizontal shifts arising essentially from Eulerian rotations of the respective plates about their own rotation pole. For practical purposes, a user working entirely within the continental territory served by NATRF2022 will perceive the transition to a multi-frame system only as a change in name and in the numerical values of coordinates, not as a conceptual change in the day-to-day use of tools.

Key Result

Todo resolved (July 2026 update). *A concrete case, published by NGS via the Beta NATRF2022 site and echoed in a sector technical report (GPS World, June 2026), now allows the qualitative estimate to be replaced with a verified order of magnitude. For CORS station COLA (Columbia, South Carolina, North American plate), the raw motion relative to ITRF2020 is approximately 14 mm/yr. Applying the EPP2022 model (Euler plate rotation), the residual displacement of NATRF2022 coordinates between epoch 2020.00 and epoch 2027.00 (seven years) is reduced to roughly 12 mm total — that is, an intra-frame residual on the order of 1–2 mm/yr, consistent with the range already given in Chapter 16 for the IFVM model. In other words, the EPP2022 model removes about 90% of the raw plate motion, leaving an intra-frame residual an order of magnitude smaller.*

Epistemic Notice

The value reported is a single case study (station COLA, South Carolina), not a systematic table of the relative Eulerian rotations among the four reference frames for the entire covered territory. Among the sources consulted, NGS has not yet published a complete table of EPP2022 parameters (poles and angular velocities) for the four plates in a directly citable numerical format; the Beta NATRF2022 site makes them available in interactive/graphical form. The order of magnitude (mm/yr, with larger residuals — over 2 mm/yr — near plate boundaries, such as western Washington) is nonetheless now verified against a primary source, unlike the previous purely qualitative formulation.

2.3 Why the distinction matters for cartography

From the standpoint of cartographic distortion theory — the methodological thread running through this volume and through the *No Map Is Best* series — the decomposition into four reference frames is interesting because it shifts the problem of spatial consistency from a single global compromise (one rigid datum, optimized for the entire continent) to four local compromises, each optimized for the kinematics of its own plate. It is the same principle, applied to the geodetic reference rather than to the projection, that motivated the introduction of *low-distortion projection zones* in the new State Plane Coordinate System (Chapter 19): giving up a single global solution in exchange for a larger number of local solutions, each with reduced distortion within its own domain of validity.

Chapter 3

Euler Poles and the Rotation Matrix Between the Ideal Frame and the Plate-Fixed Frame

3.1 Why a "plate-fixed frame" requires explicit mathematics

Chapter 2 introduced, in qualitative terms, the idea that each of the four new reference frames rotates rigidly together with its own tectonic plate. NGS Blueprint Part 1 (NOAA Technical Report NOS NGS 62) formalizes this idea with a relatively compact apparatus of linear algebra, which is worth reproducing in full: it is the mathematical core of the entire geometric modernization effort, and anyone writing about cartographic distortion theory without mastering it risks treating NATRF2022 as an abstraction rather than as the constructed object it actually is.

3.2 The Euler pole

The horizontal motion of most points on a tectonic plate, relative to an ideal global frame such as the ITRF, can be modeled as a rotation about a geocentric axis passing through a fixed point on the Earth's surface — the plate's *Euler pole*. Points closer to the pole move more slowly in terms of linear velocity (cm/yr); points farther away move faster; but all share the same angular velocity $\dot{\omega}_0$. The Blueprint stresses an important methodological point: no plate is perfectly rigid, and once the Eulerian rotation component has been removed from the velocities observed at CORS benchmarks, residual "non-Eulerian" velocities remain — some random, others systematic (for example in the Northeastern United States) — on the order of 1–2 mm/yr in stable areas, but considerably larger near plate boundaries (western California, Oregon, Washington) or where signals of glacial isostatic adjustment (GIA) are present.

3.3 Building the transformation: from RF1 to RF3

The Blueprint builds the relationship in three steps, introducing two purely auxiliary intermediate frames (RF2, RF3), for the sole purpose of making the rotation about the Euler pole algebraically simple.

Let RF1 be the ideal frame, with time-dependent ECEF Cartesian coordinates (X_1, Y_1, Z_1). Let θ_0 be the co-latitude and λ_0 the longitude of the Euler pole in RF1, and $\dot{\omega}_0$ the angular velocity of the plate about that pole.

Step 1 — rotation about the Z_1 axis by an angle λ_0, to bring the Euler pole into the X_2-Z_2 plane:

$$\begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix}_t = R_1^{\lambda_0} \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix}_t .$$

Step 2 — rotation about the Y_2 axis by an angle θ_0, to align the Z_3 axis with the Euler pole axis:

$$\begin{pmatrix} X_3 \\ Y_3 \\ Z_3 \end{pmatrix}_t = R_2^{\theta_0} R_1^{\lambda_0} \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix}_t .$$

In RF3, a point rotating rigidly with the plate has a trivial time dependence: a simple rotation about Z_3 by an angle $\alpha = \dot{\omega}_0 \Delta t$:

$$\begin{pmatrix} X_3 \\ Y_3 \\ Z_3 \end{pmatrix}_t = R_3^{\alpha} \begin{pmatrix} X_3 \\ Y_3 \\ Z_3 \end{pmatrix}_{t_0} .$$

Combining the three rotations and returning to the ideal frame RF1, one obtains a single matrix M (the product of five rotations) linking RF1 coordinates at time t to those at time t_0:

$$\begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix}_t = M \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix}_{t_0} , \qquad M = \left(R_1^{\lambda_0}\right)^{-1} \left(R_2^{\theta_0}\right)^{-1} R_3^{\alpha} R_2^{\theta_0} R_1^{\lambda_0} .$$

Key Result

Imposing the two defining conditions of the plate-fixed frame — (1) the plate-fixed coordinates of a point rotating rigidly with the plate do not change over time; (2) at time t_0 the plate-fixed coordinates coincide with those of the ideal frame — one arrives at the fundamental operational relation linking Cartesian coordinates (x, y, z) in the plate-fixed frame to the ideal coordinates (X_1, Y_1, Z_1) at the survey epoch t:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_t = M^{-1} \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix}_t + \begin{pmatrix} d \\ d \\ d \end{pmatrix}_{\Delta t} ,$$

where the vector $(d, d, d)_{\Delta t}$ represents the residual intra-frame velocities (Chapter 16). In the absence of such residuals, it can be shown algebraically that the plate-fixed coordinates remain constant over time — precisely the goal of adopting a plate-fixed system.

3.4 Why it is not a pure 14-parameter Helmert transformation

An easy conceptual error, especially for those familiar with classical 7- or 14-parameter Helmert transformations, is to directly equate the relation M^{-1} with a standard Helmert transformation. The Blueprint devotes an entire section to clarifying that it is not: in the classical 14-parameter form (Bursa-Wolf), coordinates in one frame are referred to a fixed reference epoch t_0, while in the second frame coordinates and velocities are expressed at the survey epoch t. In the Eulerian relation derived here, by contrast, both sides of the equation share the same epoch t — one is not transforming toward a fixed reference epoch, but between two frames that share the same instant in time.

Under the small-angle approximation ($\cos\alpha \to 1$, $\sin\alpha \to \alpha$), it is nonetheless possible to rewrite M^{-1} as a "degenerate" 14-parameter transformation, in which 11 of the 14 parameters are identically zero (no translation, no scale factor) and the remaining three coincide with the angular velocities about the three axes of the ideal frame:

$$\dot{\omega}_{X_1} = \dot{\omega}_0 \cos\lambda_0 \sin\theta_0, \qquad \dot{\omega}_{Y_1} = \dot{\omega}_0 \sin\lambda_0 \sin\theta_0, \qquad \dot{\omega}_{Z_1} = \dot{\omega}_0 \cos\theta_0.$$

Epistemic Notice

Chapter 13 already observed, in qualitative terms, that the NAD83→NATRF2022 transition does not reduce to a simple 14-parameter Helmert transformation. This chapter now provides the precise algebraic justification: the structural difference between equations (20) and (21) of Blueprint Part 1 — respectively, coordinates at the same epoch on both sides versus coordinates at different epochs — is precisely the reason why the analogy, however instructive, is not a formal identity.

3.5 From angular velocity to millimeters per year

The Euler pole formalism above is expressed in angular terms ($\dot{\omega}_0$, typically in degrees or radians per million years); the case study reported in Chapter 2 (station COLA, ∼14 mm/yr raw motion) is expressed in linear terms. The two are related, for a point at angular distance θ from the Euler pole (its co-latitude in the pole-centered frame RF3), by the standard rigid-rotation velocity formula

$$v = R\,\dot{\omega}_0 \sin\theta,$$

where R is the Earth's mean radius and v is the resulting linear velocity, tangent to the small circle of constant θ centered on the pole. Points near the Euler pole itself ($\theta \to 0$) move slowly regardless of $\dot{\omega}_0$; points on the "equator" of the rotation ($\theta = 90°$) move fastest. This is the same relation, applied to a tectonic plate's own rotation pole rather than to the Earth's geographic rotation axis, that governs the familiar fact that linear velocity due to Earth's rotation vanishes at the geographic poles and is maximal at the equator — and it is the formula that, applied station by station across a plate, produces the residual-velocity field that Chapter 16 models empirically (IFVM) rather than analytically (HTDP).

3.6 A geodetically relevant detail: the Caribbean and Mariana poles remain poorly known

It should be noted, for historiographic completeness, that Blueprint Part 1 explicitly acknowledges an asymmetry in the quality of the data available for the four Euler poles: while the poles of the North American and Pacific plates were already, at the time the document was drafted (2017), relatively well determined thanks to decades of GPS data, the poles of the Caribbean and Mariana plates were only weakly constrained, requiring substantial further work to reach adequate accuracy. In light of the sources consulted for this volume, this asymmetry in the quality of the underlying data across the four plates is recorded here as a documented feature of the 2017 design baseline; whether it was fully overcome by the time of the eventual official release is a question about that release's own record, not about the design process this chapter describes, and lies outside this volume's synchronic scope.

Chapter 4

Beyond the Continent: PATRF2022, CATRF2022, MATRF2022, and the U.S. Insular Areas

4.1 Three frames left in the background

Chapters 2 and 3 introduced the four-frame architecture of the modernized NSRS and worked out, in some quantitative detail, the case of NATRF2022 — the frame covering the contiguous United States, continental Alaska, and most of Canada. The other three frames, PATRF2022, CATRF2022, and MATRF2022, have so far appeared only as names in a list. This is not a proportionate treatment: while the population and economic activity anchored to those three frames is a small fraction of the NATRF2022 total, the underlying geodetic problem they solve is, if anything, more acute, since every territory they cover sits closer to an active plate boundary than does the stable interior of North America.

4.2 PATRF2022: Hawaii, American Samoa, and the Pacific plate

The Pacific Terrestrial Reference Frame of 2022 covers Hawaii, American Samoa, and other US-administered islands situated on the Pacific plate, excluding those portions of Alaska that remain on the North American plate. Unlike NATRF2022, whose stable interior spans most of a continent, PATRF2022's covered territory consists entirely of oceanic islands near, or straddling, plate boundaries: NGS's own technical description warns that while points in the stable interior of the Pacific plate should evolve slowly in the frame, this is by no means guaranteed island-wide, and localized volcanic or tectonic deformation can produce non-negligible residual motion even after the Eulerian plate rotation has been removed.

4.3 CATRF2022: Puerto Rico, the U.S. Virgin Islands, and the Caribbean plate

The Caribbean Terrestrial Reference Frame of 2022 covers Puerto Rico, the U.S. Virgin Islands, and other zones on the Caribbean plate. The Caribbean plate is a comparatively small plate bounded by significant transform and subduction margins (notably along its

northern edge, where the North American and Caribbean plates interact), and — as already noted in Chapter 3 in connection with Blueprint Part 1's own historiographic caveat — the Euler pole for the Caribbean plate was, as of the Blueprint's 2017 drafting, only weakly constrained by the GPS data available at the time, in contrast to the comparatively well-determined North American and Pacific poles.

4.4 MATRF2022: Guam, the CNMI, and the smallest of the four plates

The Mariana Terrestrial Reference Frame of 2022 is, in NGS's own words, built for "a small, crescent shaped plate between the Pacific and Philippine plates," home to Guam and the Commonwealth of the Northern Mariana Islands (CNMI). The Mariana plate is small enough that NGS's own Beta technical documentation notes the absence of a usable cartographic visualization comparable to those available for the other three plates. Precisely because of its small size and location within an actively deforming island-arc system, MATRF2022 carries the same caveat as CATRF2022 and PATRF2022, in sharper form: many points in the Mariana Islands lie along the plate margin rather than in a stable interior, and can be expected to exhibit measurable residual motion, associated with plate-boundary or volcanic deformation, even after the frame's own Eulerian rotation has been subtracted.

Frame	Tectonic plate	Principal covered territories
NATRF2022	North American	CONUS, continental Alaska, most of Canada
PATRF2022	Pacific	Hawaii, American Samoa
CATRF2022	Caribbean	Puerto Rico, U.S. Virgin Islands
MATRF2022	Mariana	Guam, Commonwealth of the Northern Mariana Islands

Table 4.1: The four 2022 terrestrial reference frames and their principal covered territories, per NGS's SPCS2022 zone-design procedures and Beta frame documentation.

Epistemic Notice

NGS's own EPP2022 (Euler Pole Parameters) values for all four plates are, according to the Beta NATRF2022 site, available for download, with a machine-readable test dataset for software developers to be released via GitHub after internal review. As of the sources consulted for this volume, the numerical parameter tables for PATRF2022, CATRF2022, and MATRF2022 specifically — as opposed to the single NATRF2022 case study already reported in Chapter 2 (station COLA) — have not been independently verified against a directly citable, stable primary source; this chapter therefore reports the qualitative and structural picture (which islands belong to which frame, and the generic plate-margin caveat) rather than plate-specific numerical rotation rates, consistent with this volume's no-invented-data discipline.

4.5 A quieter but no less real problem: legacy vertical datums

The geometric picture (which frame, which plate) is only half the story for the insular territories: each has historically used its own local vertical datum, generally tied to short tide-gauge records rather than to a continental leveling network, and each therefore requires its own transformation path into NAPGD2022. According to NGS's VERTCON 3.0 transformation grids, released ahead of the modernized system specifically to support this transition, the legacy vertical datums involved are GUVD63 and GUVD04 for Guam, NMVD03 for the CNMI, PRVD02 for Puerto Rico, VIVD09 for the U.S. Virgin Islands, and ASVD02

for American Samoa — five distinct historical references for five distinct territories, each converging on the single NAPGD2022 geopotential datum discussed in Chapters 7–10.

Epistemic Notice

Hawaii is a partial exception worth flagging precisely because it breaks the pattern: according to the same VERTCON 3.0 documentation, Hawaii has no official vertical datum, and VERTCON 3.0 accordingly provides no transformation grid for it. This is not an oversight of the modernization effort but a pre-existing gap in the legacy NSRS that the modernized system inherits rather than creates — an instructive reminder that "replacing an old datum" presupposes that a single old datum existed to be replaced, an assumption that does not hold uniformly across every US territory.

4.6 Why the insular case matters beyond its own footprint

From the distortion-theory perspective that runs through this volume, the insular territories are a useful limiting case rather than a mere administrative footnote: they show what the four-frame architecture looks like when the "stable plate interior" assumption underlying each frame's Euler-pole simplification is least available. Where NATRF2022 can treat almost the entirety of its covered territory as effectively rigid, with deformation confined to well-known boundary regions (western North America, as discussed in Chapters 3 and 16), PATRF2022, CATRF2022, and especially MATRF2022 cover territories that are, in a meaningful sense, mostly boundary. The four-frame solution does not fail in these cases, but it operates closer to the edge of its own working assumptions — a point worth bearing in mind for any reader tempted to treat the Euler-pole rotation model, introduced in Chapter 3 via the well-behaved CONUS example, as uniformly exact across the entire modernized NSRS.

Chapter 5

Anchoring to ITRF2020

5.1 A requirement of international consistency

An aspect of the modernization project easily overlooked by a reading confined purely to US geodesy is its explicit anchoring to the International Terrestrial Reference Frame 2020 (ITRF2020), the global reference system maintained by the International Earth Rotation and Reference Systems Service (IERS). According to official NGS documentation, all four new North American reference frames (NATRF2022, PATRF2022, CATRF2022, MATRF2022) are defined as derivations of ITRF2020, with differences limited to small horizontal shifts.

This represents a shift in institutional posture relative to NAD 83, which, although historically aligned approximately with international systems, did not share their origin by construction. The choice to explicitly anchor the new system to ITRF2020 — also confirmed in the official NGS FAQs, which specify that the new terrestrial reference frames will be defined relative to ITRF2020 — responds to a need for full interoperability with the rest of the geodetic world, at a time when satellite positioning (GPS, GLONASS, Galileo, BeiDou) is by its nature a global rather than a national infrastructure.

Key Result

The abstract 14-parameter transformation written out in Chapter 13 has, for the ITRF2014→ITRF2020 pair specifically, an official published numeric instantiation, which is worth reproducing as a concrete anchor for the formula. The IERS/IGN combination center reports the following parameters (ITRF2014 minus ITRF2020) at epoch 2015.0, together with their annual rates:

	T_X	T_Y	T_Z	D	R_X	R_Y	R_Z
value (2015.0)	-1.4 *mm*	-0.9 *mm*	1.4 *mm*	-0.42 *ppb*	$0.00''$	$0.00''$	$0.00''$
rate (per year)	0.0	-0.1 *mm*	0.2 *mm*	0.00	$0.00''$	$0.00''$	$0.00''$

Two features of this real-world table are worth noting explicitly. First, all three rotation parameters are exactly zero, by construction: ITRF2020's orientation was defined so as to have zero rotation and zero rotation rate relative to ITRF2014 over a 131-station core network (the "small horizontal shifts" claim above, made numerically precise). Second, every translation and scale parameter is at the millimeter or sub-ppb level — three to four orders of magnitude smaller than the NAD83→NATRF2022 shift discussed in Chapter 23 (1–4 m). This magnitude contrast is itself informative: it shows that the ITRF2020 anchoring described in this chapter introduces negligible additional distortion of its own, and that essentially all of the shift users will experience comes from the NAD83→NATRF2022 step, not from NATRF2022's own anchoring to ITRF2020.

5.2 The intermediate integration: a detail often overlooked

Even before the full release of the new datums, NGS planned an intermediate step, often omitted from popular accounts: the integration of ITRF2020 into all products and services of the current system (NAD 83/NAVD 88), planned for late 2024 or early 2025, precisely to ensure that the NSRS remained consistent with accepted international standards even during the transition period. This detail is methodologically interesting: it shows that the modernization is not a single event (a "datum-change day"), but a process of gradual alignment, in which the legacy system itself is updated to remain compatible with the international standard while its complete replacement is being prepared.

5.3 The 2020.00 reference epoch

Consistent with the anchoring to ITRF2020, the reference epoch chosen for the coordinates of the modernized system is fixed at 2020.00 — confirmed both in the official FAQs and in Blueprint Part 2. It should be stressed that this is not the same thing as the year "2022" appearing in the names of the various components (NATRF2022, GEOID2022, etc.): as will be clarified in Chapter 24, the number "2022" in the names is purely conventional and carries no scientific or temporal meaning, whereas epoch 2020.00 is the true temporal reference against which the static coordinates are computed and against which dynamic variations are measured.

Part II

The New Vertical Datum

Chapter 6

GRAV-D and the Gravimetric Construction of the Geoid

6.1 Origins of the project

The Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project began in 2007, when NGS acquired its first airborne gravimeter and formalized, by 2008, a Ten-Year Plan setting the replacement of NAVD 88 with a vertical datum founded on a gravimetric geoid model as its goal. The underlying idea, explained in NGS Blueprint Part 2, is simple to state but radical in its consequences: if GNSS ellipsoidal heights are accurate to the centimeter everywhere across the territory, and if it is possible to build a geoid model of comparable accuracy, then orthometric heights no longer need to depend on a network of physically leveled benchmarks subject to uncontrolled movement — they can be derived anywhere, in real time, from GNSS plus geoid.

6.2 From GEOID93 to hybrid geoids

The history of geoid modeling in the United States, reconstructed in Appendix A of Blueprint Part 2, shows a path of progressive refinement: the GEOID90 and GEOID93 models, based on gravimetric data and pure theory, were soon found to depart by several meters from NAD 83/NAVD 88 data — a discrepancy attributable partly to the non-geocentricity of NAD 83, partly to regional biases in NAVD 88. The solution adopted from 1996 onward was the construction of "hybrid geoids" (starting with G96SSS/GEOID96): models that start from a purely gravimetric geoid but are then corrected to fit existing NAD 83/NAVD 88 GNSS and leveling data. This compromise worked well for twenty years, but by construction it ties the geoid model to the very defects of the datum it is meant to replace.

Key Result

GRAV-D breaks this compromise: the new GEOID2022 is built as a purely gravimetric model, not hybridized with NAVD 88 leveling data, so as to avoid inheriting its structural biases.

6.3 From gravity anomalies to geoid: Stokes' formula

The GSVS campaigns compare heights, but the underlying computation that turns raw gravimetric and satellite data into a geoid grid rests on a formula older than any of the technologies discussed in this chapter. Where Bruns' formula (Appendix A) expresses the geoid undulation N in terms of the disturbing potential T, Stokes' formula (Stokes, 1849

— the same 1849 result already noted in Appendix B as the historical origin of the geoid concept) expresses T, and hence N, directly in terms of gravity anomalies Δg observed over the whole Earth:

$$N = \frac{R}{4\pi\gamma} \iint_{\sigma} \Delta g(\varphi', \lambda')\, S(\psi)\, d\sigma,$$

where R is a mean Earth radius, γ mean normal gravity, Δg the gravity anomaly at a running point (φ', λ'), ψ the angular distance between that point and the evaluation point, $S(\psi)$ the Stokes kernel function, and the integral runs over the entire sphere σ.

Epistemic Notice

Stokes' formula requires gravity data over the *entire* Earth, a requirement no real survey can satisfy exactly; in practice it is combined with the spherical harmonic model (which supplies the long-wavelength, global part of the signal) through a remove-compute-restore procedure, using only local gravity, terrain, and airborne data (GRAV-D) for the short-wavelength residual. This is the mathematical reason, beyond the purely administrative one already discussed, why the airborne GRAV-D campaigns specifically targeted *data-sparse* regions such as the US coastline (Chapter 6, GSVS11 result): filling a gap in the local Δg input degrades the Stokes-formula output precisely where that gap exists, and nowhere else — which is exactly the geographically concentrated benefit GSVS11 measured empirically.

6.4 The three validation campaigns (GSVS)

To quantify the actual benefit brought by GRAV-D data, NGS conducted three independent Geoid Slope Validation Surveys (GSVS), each roughly 300 km long, combining GPS, leveling, gravimetry, and deflection-of-the-vertical measurements, across three terrain types:

Survey	Terrain	Accuracy without GRAV-D	Accuracy with GRAV-D
GSVS11 (Texas)	flat, coastal	1–3 cm	1 cm
GSVS14 (Iowa)	inland plain	2–4 cm	2–4 cm
GSVS17 (Colorado)	mountainous	3–5 cm	3–5 cm

Table 6.1: Differential geoid accuracy, with and without GRAV-D data, for the three GSVS campaigns (source: NGS Blueprint Part 2, §11.1).

The most significant result — and counterintuitive relative to the naive expectation that more data always yields uniform improvement — is that the benefit of GRAV-D was concentrated almost entirely in flat coastal areas, where a known gap in gravimetric data existed along the coastline. In mountainous terrain (Colorado) and on the inland plain (Iowa), the addition of airborne data did not produce a statistically significant improvement, a result that prompted NGS to launch an investigation into its own geoid-modeling techniques, temporarily suspending production of the annual "experimental geoid" (xGEOID).

Epistemic Notice

The table above is the same one cited in Blueprint Part 2 as a "generalized rule of thumb"; the document itself warns that the final GEOID2022 model will include formal, geographically dependent accuracy estimates, calibrated against these empirical values but not necessarily identical to them.

Chapter 7

NAPGD2022: Architecture of the New Geopotential Datum

7.1 Four interrelated components

The North American–Pacific Geopotential Datum of 2022 (NAPGD2022), as defined in NGS Blueprint Part 2, is not a single product but a system of four time-dependent, mutually consistent components:

- **GM2022** — a global spherical harmonic model of the Earth's gravitational potential field, developed in collaboration with the National Geospatial-Intelligence Agency as an update to the EGM2020 model, up to degree and order 2190;
- **GEOID2022** — regional grids of geoid undulation;
- **DEFLEC2022** — regional grids of deflection of the vertical;
- **GRAV2022** — regional grids of interpolated surface gravity.

Each of these components is in turn split into a static part (fixed at epoch 2020.00, with prefix "S": SGM2022, SGEOID2022, etc.) and a dynamic part, which captures significant secular and episodic changes (prefix "D"). The three geographic regions covered by the gridded models are North America (including CONUS, Alaska, Hawaii, Canada, Mexico, Central America, the Caribbean, and Greenland), Guam/CNMI, and American Samoa.

7.2 The value W_0: a scientific choice that is also a diplomatic one

The choice of the gravitational potential value W_0 that defines the geoid surface is anything but trivial: alternative values have been proposed by various international bodies (IAG, IAU/IERS/BIPM, and others). NGS resolved the question empirically, comparing mean dynamic ocean topography (MODT) — which along the North American Atlantic coast varies by more than 1.5 meters between the warm, fast Gulf Stream and the cold, dense Labrador Current — at nearly two hundred tide gauges in the US and Canada. The mean residual value, after removing the estimated MODT, confirmed the value already adopted by the IAU, IERS, and BIPM:

$$W_0 = 62\,636\,856.0 \ \mathrm{m^2 s^{-2}}.$$

This empirical agreement between NGS and the Canadian Geodetic Survey enabled the adoption of a common value for the entire continent, avoiding geodetic fragmentation along the US-Canada border.

Key Result

Table of scientific choices fixed for the initial release of NAPGD2022 (v01), according to Blueprint Part 2, § 12:

- *Tide system:* tide free
- W_0 *of GEOID2022: 62 636 856.0* m^2s^{-2}
- *Epoch of SGEOID2022: 2020.00*
- *Reference frame: ITRF2020*
- *Ellipsoid (a, f): GRS 80*
- *Maximum degree of GM2022: 2190 (spherical harmonics)*
- *SGEOID2022/SDEFLEC2022 grid spacing: 1 arcminute*
- *Grid format: GeoTIFF; interpolation: biquadratic*

7.3 Why the orthometric height inherits more uncertainty than the ellipsoidal height

A subtle but central point for anyone who needs to correctly propagate uncertainty in a cartographic analysis: while the GRS 80 ellipsoid is treated as a convention free of its own uncertainty (the coordinates φ, λ, h derived from a GNSS survey acquire no additional error from the mere fact of being referred to GRS 80), the GEOID2022 geoid is *not* treated as error-free. The final orthometric height combines the uncertainty of the ellipsoidal height and that of the geoid model in quadrature:

$$\sigma_{H_{\mathrm{NAPGD2022}}}(t) = \sqrt{\sigma_h^2(t) + \sigma_{N,\mathrm{GEOID2022}}^2(t)}.$$

This is, according to NGS documentation, the first time that a geographically dependent error model for the geoid has been explicitly incorporated into the uncertainty calculation for the system's official orthometric heights.

Chapter 8

NAPGD2022 in International Context: IHRS, EGM, and Neighboring Vertical Datums

8.1 A national datum in a world of global standards

Chapter 7 introduced GEOID2022 as the zero reference surface for orthometric heights in the modernized NSRS. But GEOID2022 does not exist in isolation: Blueprint Part 2 devotes an explicit section (§ 9.1) to its relationship with other reference surfaces used around the world, an aspect that a treatment focused exclusively on the United States would risk failing to account for.

- **Global Mean Sea Level (GMSL)** — the static component SGEOID2022 is built to best fit GMSL at epoch 2020.00; the dynamic component DGEOID2022 tracks changes in the shape of the geoid over time, but does not incorporate the rise of GMSL itself (about 3 mm/yr), by construction (see the threshold mechanism discussed in Chapter 9).

- **Local Mean Sea Level (LMSL)** — can behave quite differently from GMSL, even between nearby coastal locations. The link between NAPGD2022 heights and LMSL heights (relevant for navigation and flood risk) will be established via GNSS at tide gauges, in collaboration with NOAA's Center for Operational Oceanographic Products and Services (CO-OPS).

- **International Great Lakes Datum (IGLD)** — a particularly instructive case: the current realization, IGLD 85, shares the same starting geopotential numbers with NAVD 88, while not being numerically identical to it, since IGLD 85 was corrected to fit the water levels observed at gauging stations during a standard seven-year observation period centered on 1985. The new realization, IGLD2020, will be centered on the 2020 water-level observation period and made consistent with NAPGD2022 — but will not be available until that observation period concludes (end of 2023, according to the original planning).

- **International Height Reference System (IHRS)** — the global standard that has been under realization for over a decade by the International Association of Geodesy, not yet fully realized at the time this volume was written. Once it is, NGS anticipates an offset (bias) relative to GEOID2022, along with possible additional high-frequency

terms; a conversion between the two systems will be provided in all NGS products and services as soon as it becomes available.

- **EGM96, EGM2008, EGM2020** — the three global spherical harmonic models produced by the National Geospatial-Intelligence Agency (NGA) over three decades. NGS plans to provide direct comparisons between GEOID2022 grids and those derived from these three models, in areas where GEOID2022 is defined, in collaboration with NGA.

Key Result

Once realized, the relationship between the two systems will take the standard form used throughout physical geodesy for comparing regional and global height reference surfaces:

$$N_{\mathrm{IHRS}}(\varphi,\lambda) = N_{\mathrm{GEOID2022}}(\varphi,\lambda) + \delta N_0 + \delta N_{\mathrm{hf}}(\varphi,\lambda),$$

where δN_0 is a constant offset (a datum-level bias, arising chiefly from differing conventional W_0 choices and reference epochs between the two systems) and $\delta N_{\mathrm{hf}}(\varphi,\lambda)$ a geographically varying, generally smaller, high-frequency residual term reflecting differences in the underlying gravimetric data and modeling choices. This is the same additive structure already used, in Chapter 7, to combine ellipsoidal-height and geoid-model uncertainties in quadrature, now applied instead to a systematic (not random) discrepancy between two independently realized equipotential surfaces.

8.2 Why this multiplicity of systems is not a flaw

Epistemic Notice

A reader accustomed to thinking of cartography in terms of a single "geodetic truth" might read this multiplicity of mutually non-identical height systems — GMSL, LMSL, IGLD, IHRS, EGM, NAPGD2022 — as a sign of inconsistency. It is not: each system answers a different functional requirement (coastal navigation, Great Lakes water management, global scientific standard, national cadastral cartography), and NGS's responsibility, as spelled out in the Blueprint, is to provide documented transformations among these systems, not to claim that a single standard could replace them all.

8.3 Coordination with Canada and Mexico

One final noteworthy element, often overlooked by a purely US-centered reading of the modernization: GEOID2022 will not be an NGS-exclusive product. The Blueprint specifies that the final model will be a joint effort of the National Geodetic Survey, the Canadian Geodetic Survey, and Mexico's Instituto Nacional de Estadística y Geografía (INEGI), with the declared goal of producing a single shared model for the entire modernized North American system, rather than three distinct and potentially inconsistent national models at the borders. This trilateral cooperation — discussed at greater length in Chapter 28 — is consistent with the anchoring to ITRF2020 discussed in Chapter 5: the NSRS modernization is not an isolationist project, but one explicitly designed for interoperability, both at the continental and at the global level.

Chapter 9

Quantifying the Discrepancy: Bias, Tilt, and Replacement Thresholds

9.1 The bias and tilt of NAVD 88, in figures

As anticipated in Chapter 1, the comparison between heights derived from gravimetric satellites (GRACE, around 2005; GOCE, around 2010) plus GNSS (roughly 1990–2005) and the original NAVD 88 heights (surveyed by leveling between about 1930 and 1990) revealed, across roughly 25,000 points in the NAVD 88 network that also have a GNSS-derived height:

- a mean bias of **50 centimeters** across the contiguous United States (CONUS);
- a **tilt of roughly one meter** along the line from the Pacific Northwest to southern Florida.

Epistemic Notice

Blueprint Part 2 explicitly warns that these 25,000 points are not representative of the hundreds of thousands of other leveled points in the NAVD 88 network that were never surveyed with GNSS: it is therefore not known whether they have moved, been destroyed, or remained perfectly stable. The reported bias/tilt figure is thus an estimate — the best available, but not an exhaustive measurement of the entire network.

For Alaska, the situation is different and must be treated with interpretive caution: the tilt observed in the experimental grid does not reflect a genuine tilt of the NAVD 88 datum, because the NAVD 88 network was never extended into western Alaska and was extended only marginally into eastern Alaska. The apparent southwest/northeast tilt in that region is therefore a statistical artifact caused by extrapolation into a data-sparse area, not a real geodetic phenomenon attributable to the datum.

9.2 The future replacement threshold

An aspect rarely discussed in popular literature, but of considerable methodological interest, concerns what will happen *after* NAPGD2022. Because the classical definition of the geoid ties it to global mean sea level (GMSL), and because GMSL is continuously rising (about 3 mm/yr according to IPCC 2014, with a tendency to accelerate), NGS had to choose between two strategies:

1. letting the geoid (and hence the H=0 surface) continuously track sea-level rise, with orthometric heights in constant, slight decrease;

2. fixing the geoid at a constant W_0 value, accepting that it will progressively drift from the actual mean sea level, until the discrepancy exceeds a preset threshold, at which point the entire datum would be replaced with a new one.

NGS and the Canadian Geodetic Survey jointly adopted the second strategy, setting the replacement threshold at a potential discrepancy of 2 m^2/s^2 (equivalent to roughly 20 centimeters of GMSL rise).

Key Result

The equivalence between a potential discrepancy ΔW and a height ΔN is not a rounded approximation but a direct application of Bruns' formula (Appendix A), $\Delta N = \Delta W/\gamma$, with mean gravity $\gamma \approx 9.8\ m/s^2$ at the Earth's surface:

$$\Delta N = \frac{\Delta W}{\gamma} = \frac{2\ m^2 s^{-2}}{9.8\ m\ s^{-2}} \approx 0.204\ m \approx 20\ cm.$$

The same formula, applied to the stated rate of GMSL rise (~ 3 mm/yr), gives the corresponding rate of potential drift, $\dot{W} \approx \gamma\, \dot{N} \approx 9.8 \times 0.003 \approx 0.029\ m^2 s^{-2}/yr$, and therefore a time-to-threshold of $2/0.029 \approx 68$ years — squarely inside the "60 to 70 years" figure NGS itself reports below, confirming that the two numbers are mutually consistent rather than independently rounded.

Key Result

*At the current rate of rise (3 mm/yr), NGS expects NAPGD2022 to be replaced by a new geopotential datum roughly **60 to 70 years** after release. It should be noted that minor version updates (for errors or new gravimetric data, e.g. NAPGD2022 v02) do not require a name change: only crossing the 20 cm GMSL threshold would trigger the introduction of a new name (e.g. NAPGDyyyy).*

9.3 Implications for distortion theory

Of all the chapters in this volume, this one engages most directly with the conceptual apparatus developed in the *No Map Is Best* series: the choice to "freeze" a datum for several decades, while knowing that it will progressively diverge from the underlying physical reality (rising sea level), is conceptually identical to the choice of adopting a map projection that minimizes distortion over a domain of validity limited in time or space, knowing that beyond that domain (here: beyond the 60–70 year threshold) accumulated distortion will become excessive and require a system change. The trade-off logic between operational stability and fidelity to physical reality is the same, whether one speaks of projections or of vertical datums.

Chapter 10

The Geoid Monitoring Service and the Geophysical Drivers of Change

10.1 Why the geoid, not only the crust, moves

Chapters 12 and 3 dealt with the motion of the Earth's crust — plate rotation, residual intra-frame velocities. But Blueprint Part 2 identifies a second source of temporal variation, conceptually distinct and often confused with the first: the geoid itself, as an equipotential surface defined by the distribution of Earth's mass, changes over time independently of crustal motion. To govern this second source of variation, NGS established the Geoid Monitoring Service (GeMS) in 2019, tasked with systematically investigating all potentially relevant physical processes, characterizing them along three axes: magnitude, temporal duration, and spatial scale.

10.2 Three types of change

The Blueprint conceptually distinguishes three ways in which the geoid can change, illustrated with a useful analogy:

- **Change in shape** — the surface $W = W_0$ deforms (think of a balloon being squeezed: new bulges and new depressions appear), without either the value W_0 or the mean distance from the Earth's center changing.
- **Change in size** — the volume enclosed by the geopotential field increases or decreases (the balloon inflates or deflates), without W_0 or its relative shape changing.
- **Change in W_0** — the surface that used to be called "the geoid" no longer is: a new value W_0^{new} is chosen, and the new surface $W = W_0^{\text{new}}$ becomes the geoid (two concentric balloons, one inside the other: the geoid used to be the red balloon, and it has now been chosen to be the green one).

10.3 The physical drivers, tabulated

The Blueprint provides a list — explicitly described as "illustrative, not exhaustive" — of the main geophysical processes that alter the geoid over time, with their respective magnitude and spatial scale:

Type	Example	Magnitude	Spatial scale
Shape, secular	GIA at Hudson Bay; Alaska deglaciation	2 mm/yr	>100 km
Shape, secular	Slowdown of Earth's rotation	8×10^{-17} mm/yr	pole-equator
Shape, periodic	Seasonal freeze/thaw cycles	under study	>100 km
Shape, episodic	Earthquakes, volcanic eruptions	1–10 cm	up to 200 km
Shape, transient episodic	Droughts/floods	under study	up to 500 km
Size, secular	Accretion from space dust	4×10^{-7} mm/yr	global
Size, secular	Loss of stratospheric mass	-10×10^{-7} mm/yr	global
W_0, secular	GMSL rise	1.7–3.2 mm/yr	global

Table 10.1: Geophysical drivers of geoid change, in order of decreasing relevance for the North American case (source: NGS Blueprint Part 2, Table 5-1).

Epistemic Notice

The Blueprint explicitly notes that some of these signals — marked in red in the original table — have already been judged too small for NGS to actively track (evidently the case for contributions on the order of 10^{-7}–10^{-17} mm/yr). The table reproduced here nonetheless retains their numerical values for historiographic completeness, but the reader should not infer that all the processes listed receive equal operational weight in the construction of DGEOID2022.

10.4 Quantifying "change in shape": the loading Love number

The GIA row in the table above — 2 mm/yr at Hudson Bay — is a specific instance of a general physical mechanism worth making explicit: a redistribution of surface mass (melting ice, changing water storage, post-glacial rebound of the solid Earth) perturbs the geopotential field, and hence the geoid, in a way classically described through load Love numbers. For a surface mass load expandable in spherical harmonics with degree-n coefficient $\Delta\sigma_n$, the resulting perturbation to the degree-n geopotential coefficient is

$$\Delta C_n^{\text{load}} = \frac{3\rho_w}{\rho_e(2n+1)}\left(1+k'_n\right)\Delta\sigma_n,$$

where ρ_w, ρ_e are water and mean Earth density, and k'_n the degree-n load Love number (a dimensionless, negative-valued coefficient near $n=2$ for a realistic Earth model) describing the solid Earth's own elastic and viscous response to the load — the "rebound" component of glacial isostatic adjustment, as distinct from the load's direct gravitational effect. Applying Bruns' formula (Appendix A) to ΔC_n^{load} then yields the corresponding geoid change ΔN.

Epistemic Notice

This formalism explains *why* GIA appears in the table with a decades-to-millennia response time (the viscous component of k'_n relaxes slowly, on the timescale of mantle viscosity) while an earthquake's elastic component appears nearly instantaneously: the same load-response mathematics, evaluated with the elastic versus the viscoelastic part of k'_n, governs both, but on very different timescales. The specific numerical values of k'_n are standard results from classical Earth-model literature and are not themselves NGS-specific claims; the table's magnitude column remains, as noted above, the operative NGS figure for the modernization project.

10.5 Only “reasonably measurable” signal enters the dynamic model

A practical criterion stated in the Blueprint helps distinguish what enters the dynamic component DGEOID2022: only permanent changes exceeding roughly 1 millimeter per year are explicitly incorporated into the dynamic geoid model. This threshold criterion — conceptually akin to the 20-centimeter GMSL threshold that triggers replacement of the entire datum (Chapter 9) — reflects the same general methodological principle adopted throughout the modernization: rigorously distinguishing between what is physically real (every process listed in the table exists) and what is operationally relevant (only some of those processes exceed the threshold of practical significance for a system meant to serve the entire nation).

Key Result

The fact that the Geoid Monitoring Service treats change in shape, change in size, and change in W_0 of the geoid separately — each with its own physical drivers, its own timescale, and its own threshold of operational relevance — constitutes, from the perspective of this volume, the most mature example found in NGS documentation of explicit, quantified management of epistemic uncertainty in a continental-scale cartographic reference system.

Chapter 11

From Theory to Measurement: The Dynamic Geoid in Practice

11.1 From an illustrative table to a measured map

Chapter 10 reproduced the Blueprint's table of geophysical drivers of geoid change as an explicitly "illustrative, not exhaustive" catalogue. NGS has since published an actual estimate of the dominant secular signal in that table — shape change from mass redistribution — as a geographic map rather than a single order-of-magnitude figure, computed from the NASA Goddard Space Flight Center (GSFC) mascon gravimetric model and reported in NOAA Technical Report NOS NGS 69 (*A Preliminary Investigation of the NGS's Geoid Monitoring Service*).

Key Result

Over CONUS, the estimated secular geoid rate ranges from about -1.25 *to* $+1.5$ *mm/yr; a companion map for Alaska shows a comparable range, of order* ± 1.3 *mm/yr. Both figures are small relative to NGS's stated 1 cm (1 standard deviation) accuracy goal for absolute and differential geoid undulations, but — as the source itself stresses — they accumulate over the multi-decade design life of NAPGD2022, which is precisely why they are tracked at all rather than ignored as noise.*

A worked numerical example, reported by Zilkoski from an NGS demonstration of the xGEOID20 web tool, makes the accumulation concrete rather than abstract: for two stations in Alaska, the tool computed a time-dependent geoid change of **8 mm over five years** — a rate (≈ 1.6 mm/yr) consistent with the mascon-model map above, and a first real instance of the abstract "ΔN accumulating over time" argument made on purely dimensional grounds in Chapter 10.

Epistemic Notice

The GSFC mascon-model maps (Figures 32–33 of NOS NGS 69, as reproduced in the cited GPS World column) are themselves described by NGS as a preliminary investigation, not a final, operational dynamic-geoid product; the 8 mm/5 yr xGEOID20 example is similarly a tool demonstration, not a published accuracy assessment. Both are reported here as illustrative empirical corroboration of the driver magnitudes tabulated in Chapter 10, not as a replacement for that table's sourcing.

11.2 An episodic driver, made concrete: Mount St. Helens

Chapter 10's table lists "earthquakes, volcanic eruptions" as an episodic shape-change driver, with a magnitude of 1–10 cm over a spatial scale of up to 200 km, without a named event. NGS's own popular-science account of the modernization project supplies one: the May 18, 1980 eruption of Mount St. Helens, in which the volcano's summit dropped from an elevation of 9,677 feet (2,950 m) to 8,363 feet (2,549 m) — a vertical change, at the epicenter of the event, of roughly 400 m, several orders of magnitude larger than the geoid-shape-change entry in the table, precisely because a stratovolcano's collapse is dominated by literal mass removal at the surface rather than by the deeper redistribution the table's 1–10 cm figure describes. The distinction is instructive: the table's entry quantifies the change in the equipotential surface itself, while an event like Mount St. Helens changes, first and far more dramatically, the physical elevation of the ground relative to that surface — two related but numerically very different quantities that a careless reading of the driver table could otherwise conflate.

11.3 What GEOID2022 is actually built from

Beyond the driver taxonomy, NGS has published the concrete data inventory behind GEOID2022 itself, jointly developed with the Canadian Geodetic Survey (CGS) and Mexico's national statistics and geography institute (INEGI): terrestrial gravity data, GRAV-D airborne gravity (Chapter 6), the GOCO06S satellite gravity model (Kvas et al., 2021), satellite altimetry, and a new digital elevation model, xG20DEM, itself a composite of TanDEM-X, the USGS 3DEP 1-arcsecond DEM, and MERIT. The model is distributed at 1-arcminute spatial resolution, in the tide-free system, referenced to the GRS80 ellipsoid in the ITRF2020 frame (Chapter 5), and published in the Geodetic data Grid eXchange Format (GDGF), a new Open Geospatial Consortium standard adopted for this release.

Key Result

*NGS's published estimate of GEOID2022's overall accuracy is **1–2 cm in flat terrain and 2–3 cm in mountainous terrain** — a figure that postdates, and is broadly consistent with, the earlier GSVS11/14/17 differential-accuracy table already discussed in Chapter 6, without contradicting that table's specific finding that GRAV-D's incremental benefit over pre-existing data was concentrated in flat coastal areas.*

11.4 Continued validation after release

The validation effort did not stop at the three original GSVS campaigns. In 2024, NGS, Louisiana State University, Oregon State University, and the Swiss Federal Office of Topography (swisstopo) jointly deployed astronomical cameras to measure geoid slopes along the Mississippi River between Baton Rouge and New Orleans, explicitly to validate GEOID2022 in a region chosen for its combination of sparse gravity data and active land subsidence — a deliberately harder test case than the original GSVS11 Texas transect, and one framed by NGS as an attempt to replicate the earlier campaigns' results with a lighter, faster instrument set.

In the fall of 2025, a second follow-up campaign returned to southcentral Alaska, repeating a 2021 geoid-monitoring field survey in the state's mountainous valleys. Besides validating GEOID2022's accuracy in that region, the survey explicitly measured the accumulated change in orthometric heights since the U.S. Coast and Geodetic Survey's high-precision post-earthquake survey following the 1964 Great Alaska Earthquake — data that will feed

directly into the spatial resolution of GEOID2022's dynamic component, giving Alaska (already flagged in Chapter 9 as a special interpretive case for NAVD 88's apparent tilt) a second, independent role in this monograph as the region where the dynamic geoid is being validated against the longest available historical baseline.

Epistemic Notice

Both the 2024 Louisiana and 2025 Alaska campaigns are reported here from NGS webinar announcements and a professional-surveying trade publication (*The American Surveyor*); at the time of writing, the quantitative results of the 2025 Alaska survey specifically had not yet been published in a technical report accessible to the author, and are not claimed here beyond what the announcement itself states.

Part III

Epoch-Dependent Coordinates and the New Access Paradigm

Chapter 12

Survey Epoch Coordinates and Reference Epoch Coordinates

12.1 The sunset of the "fixed" coordinate

In the NAD 83/NAVD 88 system, a geodetic point has, conceptually, a single pair of coordinates: the one published on its NGS *datasheet*. The modernized system abandons this simplification. According to the official NGS FAQs, once the new system is published, the coordinates of a benchmark will be explicitly time-dependent, and will be published in two distinct forms:

- **Survey Epoch Coordinates (SEC)** — the coordinates of the point *exactly at the epoch when the surveying instrument occupied it*. They will be available in all four NSRS reference frames, as well as in ITRF2020 and NAPGD2022, for every point.
- **Reference Epoch Coordinates (REC)** — the coordinates estimated through a least-squares adjustment, in which all available observations are projected forward in time to the common reference epoch (the first will be 2020.00) and constrained to the CORS/IGS network.

12.2 Why the distinction is necessary

The need for this distinction stems from an unavoidable geophysical fact, discussed at length in Blueprint Part 2: geodetic benchmarks, being physically anchored to the Earth's crust, move. The motion can be secular and permanent (such as the glacial isostatic adjustment centered on Hudson Bay, on the order of a few millimeters per year), episodic and permanent (an earthquake), or episodic and transient (a multi-year drought that temporarily alters the distribution of water mass). A system that claimed to assign a single, immutable "true" coordinate to a point would ignore this physical reality; an epoch-dependent system incorporates it explicitly.

Epistemic Notice

It should be noted that the geoid itself, not only the crust, changes over time (see Table 5-1 of Blueprint Part 2 for a review of the geophysical drivers: glacial isostatic adjustment, slowdown of Earth's rotation, seasonal freeze/thaw cycles, earthquakes, accretion from space dust). The change in a point's orthometric height over time is therefore the combination of two distinct effects — variation in ellipsoidal height (geometric) and variation in geoid undulation (gravimetric) — which in the old system were not even conceptually separable with the same clarity.

12.3 The coordinate as a function of time, explicitly

The conceptual shift described above can be stated compactly. In the legacy paradigm, a benchmark's coordinate is a constant vector $\mathbf{x}_0$. In the modernized system, it is instead modeled, to first order, as

$$\mathbf{x}(t) = \mathbf{x}(t_0) + \mathbf{v}\,(t - t_0) + \boldsymbol{\varepsilon}(t),$$

where $\mathbf{v}$ is the point's velocity (plate rotation plus any intra-frame residual, Chapters 3 and 16) and $\boldsymbol{\varepsilon}(t)$ collects non-linear, episodic terms (an earthquake offset, a seasonal hydrological signal) that a purely linear velocity model cannot capture. A Survey Epoch Coordinate is simply $\mathbf{x}(t_{\text{survey}})$, evaluated once, directly from the observations made at that epoch. A Reference Epoch Coordinate, by contrast, is obtained by inverting this model: given many observations of the same or nearby points at different epochs t_i, REC production solves a (weighted) least-squares problem

$$\hat{\mathbf{x}}(t_0),\ \hat{\mathbf{v}} = \arg\min_{\mathbf{x}(t_0),\,\mathbf{v}} \sum_i w_i \left\| \mathbf{x}_i^{\text{obs}} - \left[\mathbf{x}(t_0) + \mathbf{v}(t_i - t_0)\right] \right\|^2,$$

constrained to the CORS/IGS network, and then reports the fitted position at the common reference epoch $\hat{\mathbf{x}}(t_0)$ — 2020.00 for the first release. The distinction between SEC and REC is therefore, in this formalization, exactly the distinction between a single raw data point and a fitted model evaluated at a chosen epoch.

12.4 The first REC computation, in numbers

The formalism above describes what a Reference Epoch Coordinate is; NGS has since disclosed, at the Geo Week 2026 conference (Denver, February 17–18, 2026), the actual scale of the first such computation. In a presentation by Dru Smith, NGS stated that the first iteration of REC, at reference epoch 2020.00, will assign coordinates to more than **150,000 geometric (XYZ) coordinates** and roughly **1 million geopotential coordinates** (orthometric heights), drawing on data already held in the NSRS Integrated Database together with data submitted through OPUS-Share.

Key Result

The order-of-magnitude gap between the two figures — an order of magnitude more geopotential than geometric coordinates receiving a first REC — is itself informative: it reflects the much larger historical population of leveled benchmarks (accumulated over nearly a century of differential leveling, Chapter 23) relative to the comparatively smaller set of marks that have been GNSS-occupied with sufficient rigor to support a formal geometric adjustment.

Epistemic Notice

A second NGS source — the agency's own *Key Milestones* tracking page — gives a related but not identical figure for the same milestone: geometric coordinates "at over 120,000 survey marks" estimated in ITRF2020 and the four modernized frames, against the "more than 150,000" figure presented at Geo Week 2026 and cited above; the orthometric figure ("nearly 1,000,000" marks) matches closely in both sources. The two geometric figures are not necessarily in conflict — they may report the milestone at different points in its rollout, or count slightly different populations of marks — but the author has not been able to reconcile them precisely from the sources consulted, and both are reported here rather than silently resolved in favor of one.

Blueprint Part 2 effectively summarizes the required epistemological paradigm shift: the question "what is the coordinate of this point?" must be replaced by three distinct and

equally necessary questions: what is the coordinate of this point *at this epoch*? which *version* of the datum does it refer to? with which *software version* was it computed? This threefold explicitation — time, datum version, software version — represents, from the standpoint of someone working on the history and philology of cartographic data, a leap in methodological maturity comparable to the introduction of the notion of a "critical edition" in textual philology: the datum is no longer a brute fact, but a traceable, versioned, reproducible object.

Chapter 13

Transformations: NADCON, VERTCON, and the WGS84 Case

13.1 Continuity with historical datums

A modernization project that made historical data unreachable would, from the standpoint of a historian of cartography, be a failure regardless of its technical quality. NGS has explicitly planned for continuity: the NADCON (for horizontal coordinates) and VERTCON (for vertical heights) tools will be updated to allow transformation not only between NAD 83/NAVD 88 and the new datums, but also from even older datums — the North American Datum of 1927 (NAD 27) and the National Geodetic Vertical Datum of 1929 (NGVD 29) — directly to the modernized reference frames. Upon release of the modernized system, the NGS Coordinate Conversion and Transformation Tool (NCAT) will, according to the official FAQs, allow transformation between any NGS-defined historical datum and the new datums.

13.2 The particular case of WGS84

A technical detail often overlooked, but relevant to anyone working with consumer-grade GNSS data (smartphones, drones, low-cost receivers, which typically report coordinates in WGS84): the World Geodetic System 1984 is not defined by NGS, and for this reason cannot be supported through the dedicated NADCON and VERTCON tools, which are designed specifically for NGS-maintained datums. For this case, NGS will provide, through NCAT, a new generic tool based on a 14-parameter Helmert transformation, capable of connecting any pair of reference frames, including the various realizations of WGS84 over time.

13.3 The 14-parameter transformation, explicitly

Since the qualitative reference to a "14-parameter Helmert transformation" recurs throughout this volume (Chapters 3 and 13), it is worth writing it out once, in full, as the concrete object being compared against. The time-dependent (Bursa-Wolf) form used by NCAT for frame pairs such as WGS84 realizations relates Cartesian coordinates $(X, Y, Z)_1$ in frame 1 to $(X, Y, Z)_2$ in frame 2 at epoch t via

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_2 (t) = \begin{pmatrix} T_X \\ T_Y \\ T_Z \end{pmatrix} (t) + \big(1 + s(t)\big)\, R\big(r_X(t), r_Y(t), r_Z(t)\big) \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_1 (t),$$

where $R(r_X, r_Y, r_Z)$ is the (small-angle) rotation matrix built from three small rotation angles about the three axes, $s(t)$ a scale factor, and each of the seven quantities $T_X, T_Y, T_Z, r_X, r_Y, r_Z, s$ is itself linear in time about a reference epoch t_0:

$$p(t) = p(t_0) + \dot{p}\,(t - t_0), \qquad p \in \{T_X, T_Y, T_Z, r_X, r_Y, r_Z, s\}.$$

Counting the seven quantities at t_0 plus their seven rates $\dot{p}$ gives the "14 parameters" of the name.

Epistemic Notice

The official NGS FAQs explicitly state that the NADCON and VERTCON tools contain a level of geodetic detail beyond what a simple 14-parameter Helmert transformation can capture, and that integrating the two approaches within NCAT requires "subtle and complex" logic. This is a point of methodological caution for anyone working on metric embeddings and coordinate transformations (cf. the *No Map Is Best* series, vol. III) who might be tempted to treat the NAD83→NATRF2022 transition as a simple special case of a Helmert transformation: it is not, since it includes geodetic detail corrections (non-rigid deformation, local crustal effects) that cannot be captured by a pure 14-parameter model. As Chapter 3 shows algebraically, the Eulerian plate-rotation relation M^{-1} can be rewritten under a small-angle approximation as a *degenerate* instance of the equation above, with $T_X = T_Y = T_Z = 0$, $s = 0$, and only the three rotation rates $\dot{r}_X, \dot{r}_Y, \dot{r}_Z$ non-zero — which is precisely why it resembles, without being identical to, a standard 14-parameter transformation.

13.4 The FGCS vote: a schedule that has already slipped once

Key Result

Timeline update (July 2026). *The FAQ language quoted elsewhere in this volume — an FGCS vote to approve the modernized NSRS "likely in mid 2026" — has itself been revised since those FAQs were first consulted. Reporting from the Geo Week 2026 conference indicates the vote is now anticipated in late 2026 or early 2027, with full official adoption (FGCS approval, FGDC endorsement, and the transitional Federal Register Notice) potentially extending into early 2027 to allow for a smooth handover.*

This detail bears directly on the present chapter, since the entire NADCON/VERTCON continuity story described above — old datums remaining reachable through NCAT after the transition — only becomes operative once the modernized NSRS is actually declared official. The Beta-site testing regime described in Chapter 24 therefore extends by construction: a slipping FGCS vote pushes back not the design of the NADCON/VERTCON continuity path but the date on which it starts to matter to ordinary users. NCAT's own public change-log records incremental updates to the tool as recently as July 2026, consistent with the roll-out-through-testing pattern described in Chapter 24 rather than with a completed transition.

Epistemic Notice

One further specific worth recording here rather than left only implicit in the "14 parameters" discussion above: NGS distribution of NADCON and VERTCON transformation grids for the modernized NSRS is planned to use the GGXF (Geodetic data Grid eXchange Format) file format, a still-evolving international standard, rather than the legacy binary grid formats of NADCON 5.0/VERTCON 3.0. Whether NGS's own deformation-model content within GGXF is finalized remains, per the sources consulted, an open implementation question as of mid-2026, distinct from the FGCS scheduling question addressed above.

13.5 The residual role of leveling

Even in the modernized system, classical geometric leveling does not disappear: it remains the most accurate method for determining orthometric height differences over distances up to roughly 50 kilometers. What changes radically is its role in *defining* the datum: whereas NAVD 88 was entirely constituted by the leveling network, in the modernized system leveling will no longer contribute to the definition of NAPGD2022, but will be used only for the local dissemination of accurate differential heights within the already gravimetrically defined datum. The recommended starting point for any new leveling campaign, according to NGS guidance, will be GNSS acquisition of the starting orthometric heights, thereby reversing the historical hierarchy between the two methods.

Chapter 14

Covariance Propagation Through the Fourteen-Parameter Transformation

14.1 From qualitative combination to a formal propagation law

Chapter 33 combined the geoid's uncertainty and the deformation model's uncertainty "in quadrature," on the informal grounds that the two sources are not structurally correlated. This chapter makes that step formal, for the closely related case of the fourteen-parameter (Bursa-Wolf) transformation written out explicitly in Chapter 13, by applying the standard law of propagation of errors used throughout geodetic adjustment practice (Ghilani, *Adjustment Computations*, standard reference).

14.2 The general law of propagation of errors

If a vector of output quantities $\mathbf{y}$ is a differentiable function $\mathbf{y} = f(\mathbf{x})$ of a vector of input quantities $\mathbf{x}$ with covariance matrix Σ_x, then to first order the covariance of $\mathbf{y}$ is

$$\Sigma_y = J\,\Sigma_x\,J^T, \qquad J = \left.\frac{\partial f}{\partial \mathbf{x}}\right|_{\mathbf{x}_0},$$

the Jacobian of f evaluated at the working point $\mathbf{x}_0$. When $\mathbf{y}$ depends on two independent groups of inputs, $\mathbf{x}$ and $\mathbf{p}$, with independent covariances Σ_x, Σ_p, the contributions add:

$$\Sigma_y = J_x\,\Sigma_x\,J_x^T \;+\; J_p\,\Sigma_p\,J_p^T.$$

This additive structure is the formal justification for treating independent uncertainty sources "in quadrature" (Chapter 33): quadrature combination of scalar standard deviations is exactly what this matrix expression reduces to when Σ_x, Σ_p are diagonal and J_x, J_p are themselves diagonal or otherwise simple.

14.3 Applying it to the time-dependent Helmert transformation

Recall the transformation written out in Chapter 13:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_2 (t) = \begin{pmatrix} T_X \\ T_Y \\ T_Z \end{pmatrix} (t) + \big(1 + s(t)\big)\, R\big(r_X(t), r_Y(t), r_Z(t)\big) \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_1 (t).$$

Here the output $\mathbf{y} = (X, Y, Z)_2$ depends on two independent input groups: the frame-1 coordinates $\mathbf{x} = (X, Y, Z)_1$, whose uncertainty comes from the original survey or CORS solution, and the seven transformation parameters $\mathbf{p} = (T_X, T_Y, T_Z, r_X, r_Y, r_Z, s)$ at epoch t, whose uncertainty comes from however those parameters were themselves estimated (for EPP2022/IFDM2022, from the network of CORS velocity observations underlying Chapter 16's interpolated grid). The two Jacobians are immediate from the equation itself:

$$J_x = (1 + s)\, R(r_X, r_Y, r_Z), \qquad J_p = \begin{pmatrix} 1 & 0 & 0 & 0 & Z_1 & -Y_1 & X_1 \\ 0 & 1 & 0 & -Z_1 & 0 & X_1 & Y_1 \\ 0 & 0 & 1 & Y_1 & -X_1 & 0 & Z_1 \end{pmatrix},$$

where the second matrix uses the small-angle linearization of $R(r_X, r_Y, r_Z)$ already introduced, for the closely related Euler-pole case, in Chapter 3: to first order in the small rotation angles, $R\,\mathbf{x}_1 \approx \mathbf{x}_1 + \boldsymbol{r} \times \mathbf{x}_1$, whose partial derivatives with respect to (r_X, r_Y, r_Z) produce exactly the cross-product (skew-symmetric) columns shown.

Key Result

The full propagated covariance of a transformed coordinate is

$$\Sigma_y = (1 + s)^2 R\, \Sigma_x\, R^T \;+\; J_p\, \Sigma_p\, J_p^T.$$

Two structural features follow directly from this expression, both otherwise easy to miss when the transformation is treated only as a deterministic formula (as it is in Chapter 13) rather than as a map between random variables. First, since R is a rotation (orthogonal, $RR^T = I$) and $s \approx 0$ to the precision relevant here, the first term is, to leading order, simply Σ_x itself: rotation and near-unity scaling neither inflate nor deflate the original coordinate uncertainty, they merely reorient it. Second, the second term's magnitude grows with $|X_1|, |Y_1|, |Z_1|$ — the point's distance from the geocenter — since the entries of J_p involving the rotation-rate uncertainties are linear in the coordinates themselves. A rotation-rate uncertainty of fixed magnitude therefore propagates into a larger positional uncertainty for points geometrically distant from the frame's origin than for points close to it, exactly mirroring, in covariance terms, the deterministic fact already noted in Chapter 3 that linear velocity from a fixed angular rate grows with distance from the rotation axis.

14.4 Reading Chapter 33's worked example through this lens

Chapter 33's CORS COLA illustration — a station moving at 14 mm/yr, producing an accumulated $\sim$ 0.3 ft shift by 2026 relative to the 2020.00 epoch — can now be read as a statement about the deterministic term of the transformation (J_p applied to a specific, known velocity), while the Argentine-precedent uncertainty figures cited in that same chapter ($\sim$ 5 mm stable-region, 2–3 cm high-deformation-region) are statements about Σ_p itself, the uncertainty of the rotation-rate (and residual deformation) parameters entering J_p. The propagation law derived here is what connects the two: it is not merely that both figures are "in centimeters," but that the second figure enters the total coordinate uncertainty budget

precisely through the $J_p \, \Sigma_p \, J_p^T$ term of the expression above, scaled by the specific point's distance from the frame origin and by the elapsed time since the reference epoch (since, per Chapter 3, the relevant rotation angle is itself $\dot{\omega}_0 \, \Delta t$, so Σ_p for a rotation *rate* translates into a rotation-*angle* uncertainty that grows with Δt).

Epistemic Notice

This chapter derives a standard result of geodetic error propagation theory (Ghilani, *Adjustment Computations*, and, more generally, the classical variance-covariance propagation law used throughout least-squares geodetic network adjustment) and applies it symbolically to the transformation already written out in Chapter 13. It does not report, because no source consulted for this volume supplies, an actual published numerical covariance matrix Σ_p for the EPP2022 or IFDM2022 parameters themselves; NGS's and CGS's own published uncertainty characterizations for these parameters, if and when released in that form, would be the appropriate primary source for populating the formula derived here with real numbers, a step this volume does not attempt in the absence of that source.

Chapter 15

From Benchmark to CORS Station: A Paradigm Shift in Access

15.1 Direct occupation versus continuous network

The official NGS FAQs explicitly describe this aspect as "a paradigm shift": the modernized system will be accessed primarily via satellite technology (GNSS), relying on the stations of the NOAA CORS Network (Continuously Operating Reference Stations) through the OPUS (Online Positioning User Service) service, and will be based on a time-dependent gravimetric geoid model. This replaces the historical access method, founded on the direct occupation of individual physical geodetic benchmarks.

The difference is not merely technical but conceptual: in the old paradigm, geodetic "truth" resided in a finite set of physical points, each with a known coordinate, and every new survey had to physically connect to one or more of them. In the new paradigm, geodetic "truth" resides in a continuous model (the gravitational field represented by GM2022 and its derivatives) accessible in principle at every point in space, via GNSS plus geoid, without any need for physical proximity to a historical benchmark.

15.2 The end of OPUS-Share

An instructive case study on the rigor with which NGS approached this change is the decision not to include OPUS-Share in the modernized system. The official FAQs justify this choice explicitly: OPUS-Share was never integrated with the official point coordinates in the NSRS Integrated Database (IDB), and this produced, over the years, numerous official-looking but mutually inconsistent reports, often at odds even with the coordinates officially recorded in the IDB. In the modernized system, NGS will provide exclusively official coordinates (SEC or REC) computed by NGS itself from user-contributed data, but archived in the new database, thereby correcting what is explicitly described as "the main flaw" of the old service.

Epistemic Notice

This chapter touches on a topic of broader interest for the epistemology of distributed geospatial data: the tension between opening a system to decentralized contributions (useful for coverage density) and guaranteeing the unambiguous authority of the data (necessary for legal/cadastral use). NGS chose here to partially sacrifice openness in exchange for unambiguous authority, a non-obvious design choice, potentially relevant for future comparisons with other geospatial crowdsourcing systems (e.g. OpenStreetMap), which remain outside the scope of this volume but would merit separate comparative treatment.

15.3 The scale and governance of the NOAA CORS Network

The paradigm shift described above is not merely a change in access philosophy; it also rests on infrastructure of a scale worth quantifying rather than taking for granted. According to the most recent NGS technical description of the network, the NOAA CORS Network (NCN) is a cooperative effort of more than 200 federal, state, academic, and private organizations, providing publicly accessible GNSS data from more than 2,000 CORS stations across the United States and its territories. A detail that is easy to overlook, and that further sharpens the conceptual contrast with the old benchmark paradigm, is ownership: roughly 98% of these stations are owned and maintained not by NGS itself, but by its network partners, who freely share their GNSS measurements and station metadata with NGS under its published guidelines, while NGS's own role is to analyze, archive, and distribute the resulting data free of charge.

Epistemic Notice

This cooperative, largely non-federally-owned structure is itself an instructive counterpoint to the OPUS-Share case discussed below: NGS accepted heavy reliance on externally owned infrastructure (the NCN) while explicitly rejecting externally computed, unvalidated coordinate contributions (OPUS-Share). The distinguishing factor is not ownership of hardware but control over the analytical pipeline that turns raw observations into archived, authoritative coordinates.

Of the roughly 2,000 NCN stations, a strict subset — the Foundation CORS (FCORS), already introduced in Chapter 3 in connection with the modernized system's link to the ITRF — is additionally submitted to the International GNSS Service (IGS), thereby providing the direct physical linkage between the national NSRS realization and the global reference frame.

15.4 The OPUS suite: four tools, four accuracy regimes

The paradigm-shift language used by NGS refers collectively to a family of tools grouped under the Online Positioning User Service (OPUS), not to a single monolithic service. A peer-reviewed evaluation conducted by NGS staff distinguishes four versions, each designed for a different balance between observation time and achievable accuracy: OPUS-Static (OPUS-S), for full-length static sessions; OPUS-Net, an alternative static-processing pathway; OPUS-RS (Rapid Static), designed to accept sessions as short as 15–20 minutes; and OPUS-Projects, the network-adjustment tool intended for multi-mark, multi-session GNSS campaigns tied to several CORS simultaneously.

Tool	Typical session length	Horizontal accuracy	Ellipsoidal height accuracy
OPUS-Projects	10 h (network-adjusted)	< 0.5 cm (95%)	1.3 cm (95%)
OPUS-S / OPUS-Net	4 h	< 3 cm (95%)	< 3 cm (95%)
OPUS-RS	≥ 2 h	better than OPUS-S/Net at 2 h	better than OPUS-S/Net at 2 h
OPUS-RS	< 2 h	frequently unreliable (error messages)	frequently unreliable

Table 15.1: Comparative accuracy of the four OPUS tools as a function of session duration, based on 88 ten-hour GPS sessions on 18 marks in Oregon, windowed into shorter sessions and reprocessed (Gillins, Kerr, and Weaver, 2019).

The practical implication for anyone planning a transition to the modernized system,

and a useful complement to the more qualitative account given by the NGS FAQs, is that "paradigm shift" does not mean uniform accuracy regardless of effort: a full network-adjusted OPUS-Projects solution remains, by a wide margin, the most accurate access route to the NSRS, while the convenience tools (OPUS-RS in particular) trade accuracy for speed in a manner that is quantifiable and session-length dependent, not merely qualitative.

15.5 Continuity of processing tools

It should be noted, for completeness and for the benefit of anyone planning an operational transition, that NGS has announced that OPUS-Projects 5 will not be included in the modernized system, being replaced by a new cloud-native suite called OPUS 6, while an updated version of OPUS-Static (version 5.2, later evolved) will continue to allow users to share GNSS solutions on individual benchmarks for future national adjustments. The deadline for final submissions to the current system through the legacy tools has been set at January 13, 2027 (see Chapter 24 for the full timeline).

15.6 OPUS 6: what actually replaces OPUS-Projects

The continuity plan described above can now be stated more precisely than "a new cloud-native suite called OPUS 6." At Geo Week 2026, NGS's Dan Gillins presented the tool suite as three distinct development phases, each with its own scope and minimum occupation time: **OPUS-S 5.2**, a multi-GNSS update of the existing static tool, accepting occupations of one hour or more and reporting standard-deviation estimates rather than the legacy peak-to-peak values; **OPUS 6.0**, a full rewrite of the OPUS code base as a cloud-native application, supporting single or multiple occupations on a single mark with a four-hour minimum occupation time, feeding directly into the next REC adjustment; and **OPUS 6.1**, the tool that actually replaces OPUS-Projects functionality, supporting campaign-style surveys across multiple marks in a network (with provision for roughly ten data files per mark) and explicitly built for future expansion toward classical and leveling observations, though on no announced timeframe.

Epistemic Notice

A detail confirmed only at Geo Week 2026, and worth stating plainly because it corrects an easy misreading of the continuity plan above: OPUS-Rapid Static (OPUS-RS) itself, as a distinct tool, will *not* be carried over into the modernized system — NGS's stated expectation is that the broader occupation range supported by the modernized OPUS-Static 5.2 will absorb the use cases OPUS-RS previously served, not that OPUS-RS survives under a new name.

As of the same conference, NGS had not announced a release date for OPUS 6.0/6.1, describing development as active but "not imminent... not a distant, multi-year project" either; in the interim, NGS's own recommendation to users is to rely on OPUS-Share for data submission, while cautioning — in NGS's own words, reported directly at the conference — that OPUS-Share results "should not be used as geodetic control," precisely the same authority-versus-openness tension already discussed above regarding the retirement of OPUS-Share as an *official* coordinate source.

15.7 The supporting software behind the CORS-based paradigm

NGS's own *Key Milestones* tracking page lists, alongside the user-facing tools discussed above, several lower-visibility software components whose completion is a precondition for

the CORS-based access paradigm to function at all. The Multi-Year CORS Solution version 3 (MYCS3), targeted for 2025, is intended to complete ITRF2020 coordinate functions — position plus velocity — for *every* station in the NOAA CORS Network, not merely the Foundation CORS subset already tied to the IGS (Chapter 15, first section): it is, in effect, the CORS-network-wide analogue of a single Foundation-CORS ITRF tie, extended to the roughly 2,000-station NCN as a whole. Alongside MYCS3, NGS lists three further internal software milestones: the GVX file format (2021), developed with industry input to let OPUS ingest real-time-network (RTN) data; LASER, a least-squares adjustment suite used within OPUS and other NGS modernization projects; and SPROCCET, software specifically built to project geodetic coordinates forward or backward through time — the computational engine implementing, in practice, the velocity-model formalism of Chapter 12 inside both OPUS and the REC adjustment pipeline itself.

Key Result

None of these four components (MYCS3, GVX, LASER, SPROCCET) is user-facing in the way OPUS or NCAT are, yet each is a necessary precondition for a specific claim made elsewhere in this monograph to hold operationally rather than merely in formal design: MYCS3 is what makes "every CORS station tied to ITRF2020" true rather than aspirational; SPROCCET is the actual implementation of the $\mathbf{x}(t) = \mathbf{x}(t_0) + \mathbf{v}(t - t_0) + \boldsymbol{\varepsilon}(t)$ *model of Chapter 12, not merely its textbook statement.*

A complementary, more visible 2024 milestone worth noting alongside these is GPS on Benchmarks, a crowdsourced data-collection campaign inviting surveyors and members of the public to occupy existing survey marks with GNSS specifically to support the conversion from current vertical datums to NAPGD2022 heights, with the resulting data intended for integration into the updated NCAT tool — a rare instance, within an otherwise centrally engineered modernization effort, of the OPUS-Share-style crowdsourced contribution model (Chapter 15, second section) being deliberately re-embraced for a specific, bounded purpose rather than uniformly rejected.

Chapter 16

From HTDP to the Intra-Frame Velocity Model: A Change in Philosophy

16.1 The historical approach: modeling the entire crust

For decades, NGS provided a model of horizontal motions — both plate rotation and horizontal intra-frame velocities — through the Horizontal Time-Dependent Positioning (HTDP) program. HTDP's historical purpose was to allow comparison between two GNSS surveys of the same vector (baseline between two points), carried out at different epochs, by shifting the information "in time" to a single shared reference epoch. This philosophy presupposes that geodetic control must be provided at a single reference epoch: every point has one fixed set of coordinates, and subsequent surveys are brought back to that epoch through a geophysical model of the entire crust.

Epistemic Notice

Blueprint Part 1 explicitly notes a practical limitation of HTDP rarely discussed in popular literature: the tool never supported vertical velocities, except for central Alaska. A model designed for only the horizontal component of crustal motion is, by construction, incomplete with respect to the broader problem of geodetic control stability in three dimensions.

16.2 The underlying problem: a complete geophysical model is unsustainable

To function correctly, HTDP had to incorporate geophysical crustal models for several western states and Alaska, including compression and earthquakes. Failure to fully model a seismic event translated directly into a failure to provide geodetic-quality horizontal positions at the affected control points. NGS concluded, in preparing the modernized system, that this approach is not sustainable at continental scale over the long term: a whole-crust deformation model, continuously updated to track every earthquake, every compression event, every GIA signal at every spatial and temporal scale, is — to use the Blueprint's own expression — "unmanageable and unsustainably complex."

16.3 The new approach: data, not explanations

The change in philosophy adopted for the modernized system is conceptually radical, and it is worth reporting in the terms the Blueprint itself uses to argue for it: the essential function of geodetic control is to know *where* a point is located, not necessarily to *explain why* it has moved relative to a previous survey. If two geodetic-quality surveys of the same point, conducted at different epochs, return different coordinates within the same frame, that difference is direct evidence — of error in one of the two surveys, of a difference in data quality or processing strategy, or of real movement of the point — but NGS does not consider it an essential task of the NSRS to determine which of these explanations is correct.

Key Result

*The new Intra-Frame Velocity Model (IFVM) will be built from CORS station data (*geokinematics*), not from predictive geophysical crustal models (*geodynamics*). A three-dimensionally interpolated grid of CORS velocities is simpler to produce, requires no external geophysical model, and is built entirely from internal, NGS-validated data. Preliminary tests (Saleh, personal communication cited in the Blueprint) show residual intra-frame velocities, after removing plate rotation, generally contained within 1–2 cm cumulative over a decade in stable areas — with exceptions exceeding 2 mm/yr near deformation zones, earthquakes, or rotating blocks along plate boundaries.*

16.4 Interpolating a velocity grid, explicitly

The phrase "three-dimensionally interpolated grid of CORS velocities" above describes, in operational terms, a standard bilinear interpolation. Given a velocity component (say, the north component v_N) known at the four grid nodes surrounding a query point (φ, λ), with grid spacing $\Delta\varphi, \Delta\lambda$ and normalized offsets $u = (\varphi - \varphi_0)/\Delta\varphi$, $t = (\lambda - \lambda_0)/\Delta\lambda$ within the cell, the interpolated value is

$$v_N(\varphi, \lambda) = (1-u)(1-t)\, v_N^{00} + u(1-t)\, v_N^{10} + (1-u)t\, v_N^{01} + ut\, v_N^{11},$$

applied independently to each of the three velocity components (north, east, up) at each grid node. This is deliberately the simplest possible interpolation scheme available, consistent with the "data, not explanations" philosophy described above: IFVM does not attempt to model *why* the velocity field varies between grid nodes (a geophysical question), only to interpolate smoothly *what* was observed at the surrounding CORS stations (a geometric one). A predictive geophysical model such as HTDP, by contrast, effectively replaces this interpolation step with a physical simulation of crustal deformation — more explanatorily ambitious, but also, as the Blueprint itself concedes, harder to keep accurate everywhere at once.

16.5 A shift in hierarchy: from "single truth" to "epoch of convenience"

The IFVM model will not be used for least-squares adjustments of data spanning long time intervals (a function reserved for the primary service, see Chapter 12 on SEC and REC), but will be provided as a secondary service to bring coordinates to a common "epoch of convenience," expected on a 5–10 year cadence, for the benefit of the much larger engineering and cartography community (as opposed to the narrower geodetic surveying community), which needs coordinates comparable at cartographic, not geodetic, precision.

Epistemic Notice

NGS emphasizes strongly that coordinates produced through this "time transformation" must never be used as geodetic control by those conducting precision surveys: they are useful for shifting a map from one epoch to another, for building epoch-transformation software (along the lines of NADCON), or for shifting survey positions at the cost of some loss of accuracy — but they are not conceptually equivalent to a new geodetic survey conducted at the destination epoch.

16.6 A methodological aside for the reader interested in the history of cartography

The shift from HTDP (a predictive geophysical model, oriented toward explanation) to the new IFVM (a data-driven model, oriented toward description without necessarily explaining) is, on closer inspection, the same epistemological choice implicitly made whenever a historical archive forgoes offering a single, unambiguous interpretation of a lacunose source in favor of a faithful transcription accompanied by a critical apparatus, leaving the interpretive responsibility to the user. This is not a forced analogy: both choices arise from the same awareness — that a fully explanatory model, however desirable in principle, may be more costly to maintain accurately than the additional information it provides is worth.

Chapter 17

Rigid Rotation and Strain: The Velocity Gradient Tensor Behind "Non-Eulerian" Motion

17.1 A qualitative distinction, made precise

Chapter 3 noted, in passing, the Blueprint's own qualitative acknowledgment that "no plate is perfectly rigid," with residual, non-Eulerian velocities remaining once the plate's overall rigid rotation has been removed — small (1–2 mm/yr) in stable areas, considerably larger near plate boundaries or where glacial isostatic adjustment is present. Chapter 16 then described how IFVM/IFDM2022 handles this residual field empirically, by bilinear interpolation of a CORS velocity grid, deliberately declining to explain the residual geophysically. This chapter supplies the missing conceptual link between the two: the precise mathematical sense in which a velocity field decomposes into a rigid-rotation part (fully captured by the single Euler pole of Chapter 3) and a genuinely deformational part (exactly what IFDM2022 exists to capture, and what a single Euler pole cannot, by construction, represent).

17.2 The velocity gradient tensor

Consider the horizontal velocity field $\mathbf{v}(x, y) = (v_E, v_N)$ over a local tangent-plane patch of a plate's surface, with v_E, v_N the east and north velocity components already introduced, as an interpolated grid quantity, in Chapter 16. The velocity gradient tensor is the 2×2 matrix of partial derivatives

$$L = \nabla \mathbf{v} = \begin{pmatrix} \dfrac{\partial v_E}{\partial x} & \dfrac{\partial v_E}{\partial y} \\ \dfrac{\partial v_N}{\partial x} & \dfrac{\partial v_N}{\partial y} \end{pmatrix}.$$

Any such tensor admits a unique decomposition into a symmetric and an antisymmetric part,

$$L = E + W, \qquad E = \tfrac{1}{2}\big(L + L^T\big), \qquad W = \tfrac{1}{2}\big(L - L^T\big),$$

a standard result of linear algebra applied, here, to continuum kinematics in the same manner it is applied throughout geodetic strain analysis and structural geology.

17.3 The antisymmetric part is exactly a rigid rotation

The antisymmetric part W has, in two dimensions, only one independent entry, conventionally written

$$W = \begin{pmatrix} 0 & -\dot{\omega} \\ \dot{\omega} & 0 \end{pmatrix},$$

and a velocity field of the pure form $\mathbf{v} = W\mathbf{x}$ (no symmetric part at all) is, exactly, a rigid rotation of the local patch about a point at angular rate $\dot{\omega}$ — the local, tangent-plane counterpart of the single global angular velocity $\dot{\omega}_0$ about the Euler pole introduced in Chapter 3.

Key Result

For a genuinely, perfectly rigid plate, the velocity field predicted by the Euler pole formula of Chapter 3 ($v = R\dot{\omega}_0 \sin\theta$, tangent to circles of constant angular distance θ from the pole) has, at every point of the plate, a velocity gradient tensor L that is purely antisymmetric*: $E \equiv 0$ everywhere. This is not an approximation but an exact algebraic property of rigid-body rotation fields, and it is the precise formal content of the statement "the plate is rigid": zero strain rate at every point, not merely small residual velocities at a few monitored stations.*

17.4 The symmetric part: strain rate, and what IFDM2022 is actually for

It follows immediately from the keyresult above that any nonzero symmetric part E observed in a real velocity field is, by definition, evidence of departure from rigid-plate behavior — deformation internal to the plate, not merely rotation of it. This is exactly what Chapter 3's "residual non-Eulerian velocities" are, expressed now as a tensor field rather than as a list of station-by-station anomalies: after subtracting the plate's own rigid Euler-pole rotation from the observed field, whatever velocity gradient remains is, by the decomposition above, pure E, the strain-rate tensor.

The strain-rate tensor E admits, via its eigenvalues $\dot{\epsilon}_1 \geq \dot{\epsilon}_2$ (the principal strain rates, found in the directions of E's eigenvectors, mutually orthogonal since E is symmetric), two invariant scalar quantities of direct geodetic interest:

$\dot{\epsilon}_{\text{area}} = \dot{\epsilon}_1 + \dot{\epsilon}_2 = \text{tr}(E)$ (areal dilatation rate), $\dot{\gamma}_{\max} = \dot{\epsilon}_1 - \dot{\epsilon}_2$ (maximum engineering shear-strain rate).

The first measures whether a small patch of the plate's surface is, on net, expanding or contracting (positive or negative trace); the second measures how strongly the patch is being distorted in shape independent of any area change. Both are, unlike the raw velocity components v_E, v_N themselves, invariant under the choice of local coordinate axes — a property that makes them the natural quantities for comparing deformation intensity across different regions of a plate on a common footing, exactly the comparison Chapter 33 draws qualitatively between "stable regions" and "high-deformation regions" (the Argentine precedent, and the Houston-Galveston illustration) without, there, giving the tensor machinery that makes "high-deformation" a precisely quantifiable statement.

Epistemic Notice

The Houston-Galveston case cited in Chapter 33 is, strictly, a case of dominantly *vertical* deformation (subsidence from groundwater and hydrocarbon extraction), not the horizontal tectonic strain the tensor E defined above most directly addresses; the two are related in general geodetic deformation monitoring but governed by different physical mechanisms, and this chapter does not conflate them. The clearer domestic illustration of genuinely horizontal strain-rate accumulation, per Chapter 3's own account, is the western United States plate-boundary zone (California, Oregon, Washington), where non-Eulerian residual velocities are explicitly reported as "considerably larger" than in stable areas — precisely the regime in which E, not just W, dominates the local velocity gradient.

17.5 Why a single Euler pole per plate is, by this argument, structurally insufficient

This decomposition supplies the rigorous version of a point Chapter 3 could only assert qualitatively ("no plate is perfectly rigid"): a single Euler pole, applied uniformly across an entire tectonic plate, is mathematically equivalent to asserting $E \equiv 0$ everywhere on that plate — a statement that is exactly true only for an idealized rigid body, and that real plates, subject to internal compression, extension, and localized faulting, satisfy only approximately, and considerably less well near their boundaries than in their stable interiors. IFDM2022's function, in this light, is precisely to supply the spatially varying $E(x, y)$ (together with any residual, non-strain-related noise) that a single global $\dot{\omega}_0$ cannot represent by construction, regardless of how accurately that single Euler pole is estimated.

Key Result

The formal decomposition $L = E + W$ clarifies the division of labor between EPP2022 and IFDM2022 already described operationally in Chapter 16: EPP2022 supplies the single, plate-wide antisymmetric part W (equivalently, the Euler pole and $\dot{\omega}_0$ of Chapter 3), while IFDM2022 supplies the spatially varying residual — dominated, wherever it is non-negligible, by the symmetric strain-rate part E that a rigid-body model cannot capture at any spatial resolution, however fine.

Epistemic Notice

This chapter's tensor formalism (velocity gradient decomposition, principal strain rates, areal dilatation) is standard continuum-kinematic mathematics, applied here to geodetic velocity fields in the same manner it is applied throughout the geodetic strain-rate literature (see, for a standard treatment in the crustal-deformation context, Segall, *Earthquake and Volcano Deformation*, Princeton University Press, 2010). No source consulted for this volume presents NGS's own IFDM2022 documentation in these explicit tensor terms; this chapter's contribution is to supply the rigorous kinematic vocabulary underlying the qualitative Blueprint language already reported faithfully in Chapters 3 and 16, not to report a new empirical finding about IFDM2022 itself.

Chapter 18

Alaska: Geodesy at the Edge of a Rigid-Plate Fiction

18.1 A state that breaks the modernization's simplifying assumption

Chapter 3's Euler-pole formalism, and Chapter 16's account of the shift from HTDP's whole-crust modeling to the data-driven IFVM/IFDM approach, both rest on an implicit simplifying assumption: that a named tectonic plate is, to first order, rigid, and that a single Euler pole per plate captures most of the horizontal motion a control point will experience. Alaska is the part of the U.S. landmass where this assumption is least defensible, and for that reason it recurs, piecemeal, across several earlier chapters of this volume — as the special interpretive case for NAVD 88's apparent tilt (Chapter 9), as one of two protagonists of the post-release geoid validation campaigns (Chapter 11), and, in Chapter 16, as the one region for which HTDP historically supported any vertical velocity modeling at all. This chapter draws those threads together into a single, geographically organized account of why Alaska functions, within the modernized NSRS, less as an outlying special case than as the clearest available illustration of what the plate-fixed frame architecture is actually for.

18.2 Three Alaskas, geodetically speaking

The published geophysical literature on Alaskan crustal motion, largely independent of the NGS modernization program itself, distinguishes at least three geodetically distinct regions within the state, each dominated by a different driver:

- **South-central Alaska**, where the Pacific plate actively subducts beneath the North American plate along the Aleutian megathrust. Horizontal velocities here reflect ongoing subduction loading and, episodically, coseismic and postseismic deformation from major earthquakes — most consequentially the magnitude-9.2 1964 Great Alaska Earthquake, whose post-event high-precision releveling survey by the U.S. Coast and Geodetic Survey supplies, as noted in Chapter 11, the longest historical baseline against which the 2025 GeMS follow-up campaign measured accumulated orthometric-height change.

- **Southeast Alaska**, where GPS and absolute-gravimetry studies (DeGrandpre et al., 2019; Hu et al., 2019, building on earlier work by Larsen, Sato, and Ivins) document glacial isostatic adjustment (GIA) uplift of up to approximately 3 cm/yr, among the

fastest rates of vertical crustal motion measured anywhere on Earth, driven by rapid post-Little Ice Age deglaciation superimposed on ongoing subduction-related uplift.

- **Northern and western Alaska**, thousands of kilometers from the Southeast Alaska uplift center, where the same published GPS studies document the opposite signal: measurable regional *subsidence*, modeled as forebulge collapse from the retreat of the Pleistocene Laurentide and Cordilleran ice sheets — a slow-motion, opposite-sign counterpart to the rapid uplift documented in the southeast of the same state.

Key Result

No single Euler pole, however carefully fit, can simultaneously represent subduction-driven uplift in south-central Alaska, GIA-driven uplift approaching 3 cm/yr in the southeast, and GIA-driven subsidence in the north and west. Alaska is consequently the part of NATRF2022's domain where the residual, non-rigid intra-frame motion the IFVM/IFDM machinery of Chapter 16 is designed to capture is largest in both magnitude and spatial variability, rather than a secondary correction to an otherwise adequate rigid-plate model.

18.3 An earthquake in the middle of the network: Denali, 2002

The practical consequence of treating Alaska as ordinary plate interior surfaced directly in NGS's own CORS coordinate-maintenance record. The magnitude-7.9 Denali Fault earthquake of November 3, 2002 — rupturing a strike-slip fault system that NGS's own network-maintenance documentation records as displacing the ground surface, along a fault NASA and USGS mapping places at the boundary zone between the subducting Pacific plate and North America, at long-term rates on the order of 13 mm/yr of combined lateral and vertical offset — produced a measurable, sudden coordinate discontinuity at several Alaskan CORS stations, requiring NGS to update their adopted positions and velocities outside its normal annual maintenance cycle. The episode is a small-scale preview, confined to a handful of stations rather than a whole region, of the exception NATRF2022's own beta documentation states explicitly: coordinates of points within a plate's *stable interior* evolve slowly with respect to that plate's frame, but "many points will exhibit residual motions associated with plate boundary zone deformation … or other causes," and NGS names Alaska's boundary-zone stations among the clearest instances of this caveat.

Epistemic Notice

This chapter's account of the Denali earthquake's effect on specific CORS coordinates is drawn from a general NGS network-maintenance summary describing the episode as a representative example of triggered coordinate updates, not from a station-by-station technical report; the 13 mm/yr long-term Denali Fault slip-rate figure is drawn from published structural-geology literature (Gillis et al., *Geosphere*, 2022) describing the fault's long-term geological rate, which is not the same quantity as the coseismic 2002 offset at any individual CORS monument, and the two should not be conflated.

18.4 A frame-assignment question the sources leave open

A natural question, given the above, is which of the four 2022 terrestrial reference frames actually governs Alaska. NGS's own naming-convention documentation states plainly that the four frames were chosen specifically "because they encompass the US landmass and our territories," and describes NATRF2022 as covering the North American plate, on which the great majority of the Alaskan landmass, including all CORS stations discussed above, sits.

The sources consulted for this volume do not, however, resolve in comparable detail whether any portion of the far western Aleutian chain — geographically closest to the Pacific-plate boundary the PATRF2022 frame is built around — receives a distinct frame assignment, as American Samoa and other Pacific-plate island territories do under the frame-to-territory logic already documented in Chapter 4.

Epistemic Notice

No primary NGS source consulted for this volume states explicitly, for any specific westernmost Aleutian station, an assignment to PATRF2022 rather than NATRF2022. Absent such a source, this volume records the open question rather than inferring an answer from general geographic proximity to the plate boundary, consistent with its no-invented-data standard.

18.5 What Alaska adds to the volume's overall argument

Chapter 1 framed the modernization's rationale largely around the accumulated inadequacy of a static datum for a geocentric, GNSS-native positioning environment. Alaska sharpens that argument in a way CONUS examples cannot: it is not merely that NAD83 grows stale over time everywhere, uniformly and slowly, but that a single Euler-pole rotation — the modernization's own chosen mechanism for keeping a frame's stable interior current without a full crustal model — explicitly fails to describe an entire, populous U.S. state, for reasons (active subduction, differential GIA, boundary-zone faulting) that are permanent features of Alaska's geophysical setting rather than a transient measurement gap awaiting a future data release. The IFVM/IFDM residual-velocity-grid layer of Chapter 16 is, in Alaska more than anywhere else in the modernized NSRS, doing the majority of the descriptive work; the Euler-pole rotation is doing comparatively little of it.

Part IV

Projection and Distortion: The Bridge to Cartographic Theory

Chapter 19

SPCS2022 and Low-Distortion Zones

19.1 From centralized design to participatory design

The State Plane Coordinate System (SPCS), introduced in the 1930s and later revised for the transition to NAD 83 ("SPCS 83"), is being entirely redesigned in the modernized system as the State Plane Coordinate System of 2022 (SPCS2022). Unlike previous revisions, the design process for SPCS2022 was carried out through an extensive effort of direct consultation with individual states, many of which designed their own zones autonomously, in coordination with NGS.

Key Result

Todo partly resolved (July 2026 update). *The NGS Beta SPCS2022 site itself confirms, in qualitative but authoritative terms, the structural claim underlying the 953-zone figure: every state and US territory has at least a statewide zone, most states also have a multi-zone layer covering the entire state, and some states add a further layer covering only part of the state (up to three co-existing zone layers per state) — with the number of zones per state varying considerably because many states actively co-designed their own zone layout with NGS, consistent with the participatory design process described above. The xyHt figure of 953 total zones is presented in that article as a NOAA/NGS-credited graphic rather than as the author's own count.*

Epistemic Notice

This corroborates the order of magnitude and the structural reason for it, but the exact figure of 953 (and the 67 request forms from 41 states) has still not been independently recomputed from the NGS zone-definition table itself (available at beta.ngs.noaa.gov/SPCS/zone-information.html), which was not directly enumerable from the sources consulted for this chapter. The figure is reported here as corroborated rather than as independently verified.

19.2 Low-distortion zones: the same problem, a different scale

The element of SPCS2022 of greatest interest for cartographic distortion theory is the systematic introduction of so-called *low-distortion projection zones* (LDPZ): local conformal projections, typically of small extent, designed so that the combined scale factor (projection scale multiplied by the ellipsoidal-height reduction) stays within a narrow tolerance — historically, the goal of many LDPZs is to remain within a few parts per million of linear distortion, allowing distances measured on the ground to be treated as practically equivalent to projected distances, without the need for systematic corrections during surveying or

construction.

Key Result

The "combined scale factor" at a point, the quantity LDPZ design actually minimizes, is the product of two independent effects: the projection (grid) scale factor k_{proj}, intrinsic to the map projection and the point's position within its zone, and the elevation (or "sea-level") factor $k_{\text{elev}} = R/(R+h)$, which reduces a ground distance to its equivalent at the ellipsoid surface, with R the local radius of curvature and h the point's height above the ellipsoid:

$$k_{\text{combined}} = k_{\text{proj}} \times k_{\text{elev}} = k_{\text{proj}} \times \frac{R}{R+h}.$$

The linear distortion, in parts per million, is then $\delta = (k_{\text{combined}} - 1) \times 10^6$. Classical statewide SPCS zones minimize k_{proj} alone, typically leaving δ on the order of tens to a few hundred ppm; an LDPZ instead chooses its projection axis and elevation specifically so that k_{combined} stays within a few ppm of unity at the topographic surface*, not at the ellipsoid — which is precisely what the NGS zone-design documentation means in stating that SPCS2022 zones minimize distortion "at the topographic rather than the ellipsoid surface" (Section 3 of the design methodology, Dennis 2023), a refinement relative to the ellipsoid-only criterion used for SPCS 83.*

This is, in substance, the same problem addressed in Volume I of the *No Map Is Best* series regarding azimuthal projections: the tension between a single, wide-coverage solution (the historical state-scale SPCS zones, with moderate but non-negligible distortion across their full extent) and a larger number of reduced-coverage solutions, each with near-zero distortion within its own domain. SPCS2022 explicitly institutionalizes this second strategy, giving states the option of pairing traditional statewide zones with custom-tailored LDPZ zones for specific counties, districts, or infrastructure corridors.

Key Result

SPCS2022's choice to offer both wide-coverage zones and custom-tailored low-distortion zones at the same time does not resolve the classical distortion/coverage trade-off described by map projection theory (see in particular the Jensen-Shannon-divergence analysis in Volume II of the No Map Is Best *series): it shifts it to the level of an operational choice left to the end user, rather than imposing a single compromise solution at the system level.*

19.3 A unit of measure, not just a projection

A detail often overlooked in popular accounts, but of no minor historical-cartographic interest: the modernized system will support exclusively the international foot, while the U.S. survey foot — a unit of measure slightly different from the international foot, by an amount on the order of a few parts per million, but sufficient to produce non-negligible cumulative errors over long distances — will remain supported only for legacy coordinate systems (SPCS 83/NAD83(2011)). The gradual disappearance of a dual unit of measure, a historical source of silent conversion errors in US cadastral practice, is itself a small but real contribution to reducing systemic distortion in the data-to-map chain. Chapter 29 gives the exact defining ratios, the precise deprecation date, and the practical software and metadata implications of this change in full.

Chapter 20

SPCS2022 in Numbers: Design Performance and State-Level Case Studies

20.1 The CONUS-wide design performance comparison

The theoretical distinction drawn in the previous chapter, between distortion minimized at the ellipsoid and distortion minimized at the topographic surface, is not merely conceptual: NGS itself has published an aggregate, CONUS-wide comparison of the two systems' actual design performance, presented by Michael Dennis (NGS's SPCS2022 coordinator) at a July 2023 webinar and reported by David Zilkoski in *GPS World*.

Key Result

Aggregating linear distortion across all CONUS zones, NGS reports a design performance of ±159 *ppm for the existing SPCS 83 zone layer, against* ±45 *ppm for the corresponding SPCS2022 zone layer — a reduction by a factor of roughly 3.5, achieved for a coverage criterion NGS defines as encompassing 90% of the population, 75% of cities and towns, and 50% of the total land area of a zone.*

The same source specifies the two-tier design-criterion structure underlying this result: zones designed directly by NGS were typically held to a ±50 ppm design target, while many of the low-distortion projection (LDP) zones designed by state or local stakeholders were held to a stricter ±20 ppm target. This confirms, with an actual published figure rather than a qualitative description, the participatory-design mechanism already discussed in Chapter 19: the aggregate improvement is not attributable to a single centralized redesign, but to the combination of a systematically better default (ellipsoid-to-topographic-surface criterion, applied uniformly) and a large number of locally optimized stakeholder zones pulling the distribution further down.

Epistemic Notice

The ±159 / ±45 ppm figures are read directly off Dennis's presentation slides as reproduced in the cited *GPS World* column; they are aggregate CONUS design figures, not independently recomputed by the author from the underlying zone-by-zone data. They are reported here as verified secondary reporting of a primary NGS presentation, consistent with the sourcing standard adopted throughout this monograph.

20.2 Two design philosophies, two states: Ohio and North Carolina

The participatory character of SPCS2022 design produced, in practice, two opposite state-level strategies, both well documented. North Carolina chose to retain a single statewide zone. Ohio, by contrast, designed a dense layer of 89 low-distortion projection zones covering the entire state — an LDP density of essentially one zone per county.

The practical consequence of this divergence can be shown with real, published point-level figures rather than aggregate statistics. Zilkoski's account gives worked examples computed with the Alpha version of the NGS Coordinate Conversion and Transformation Tool (NCAT):

- For a CORS station in North Carolina (NCMR, Monroe), converted to the state's single statewide SPCS2022 zone, the reported linear distortion at the mark is −54.554 ppm.
- For a CORS station in Columbus, Ohio (COLB), the auto-selected LDP zone (OH FRA-391025, the Franklin County LDP) gives a linear distortion of +8.024 ppm at the same mark.
- Recomputing the same Columbus coordinates in Ohio's own *statewide* zone instead of its local LDP — a direct, same-point, same-source comparison — the reported distortion jumps to −168.316 ppm.
- A separate worked example for a point in the Franklin LDP zone alone (not tied to a specific CORS) gives 6.725 ppm, consistent in order of magnitude with the COLB figure above.

Key Result

The Columbus, Ohio comparison is the single clearest published illustration available of what an LDP buys a user in practice: the same physical point*, converted with the* same tool*, shows* +8.024 *ppm of distortion under its local LDP zone against* −168.316 *ppm under the statewide zone covering the same location — a twenty-fold reduction obtained purely by zone choice, with no change to the underlying reference frame or geodetic observations.*

This is a real-world, numerically documented instance of the same distortion/coverage trade-off formalized in Chapter 19 and, at a more general theoretical level, throughout the *No Map Is Best* series: North Carolina accepts higher worst-case distortion in exchange for a single, simple, statewide coordinate system; Ohio accepts the administrative overhead of 89 separate zone definitions in exchange for near-uniform low distortion everywhere in the state. SPCS2022 does not adjudicate between the two: it provides the design framework and lets each state's stakeholders choose a point on the same trade-off curve.

20.3 Naming conventions and the wider stakeholder landscape

Two further state-level cases, documented independently of the Zilkoski/NCAT examples above, illustrate how widely the stakeholder-design option was taken up, and how it is administratively organized.

Wisconsin adopted a statewide zone together with a 59-zone LDP layer, published on the NGS Alpha/Beta site with a status of "final" (still described as provisional pending the official release of the modernized NSRS); the state's own name for this LDP layer, WIGGS (Wisconsin Grid-Ground Systems), is not used by NGS itself, which lists the zones under its own naming and numeric-code convention. The published parameter table for these zones records, for each LDP, the projection type, latitude and longitude of origin, scale factor at

the origin, and false easting/northing — the same parameter set used for any State Plane zone, statewide or local.

Kentucky offers a second, independently documented naming case: its own State Plane Coordinate System standards document lists a specific NATRF2022-referenced LDP, designated `KYLDP7NC-2022` in the state's own convention and cross-referenced to the NGS zone code `211007 KY NC`, alongside a six-step worked methodology for LDP design (choice of projection type and axis placement near the area centroid; scaling to a representative ground height; iterative distortion computation and refinement; and a stated preference for keeping the final zone definition simple).

Epistemic Notice

The existence, naming, and NGS cross-reference code of the Kentucky and Wisconsin LDP zones discussed above are independently documented in state-published sources. The specific numeric defining parameters of these particular 2022-generation zones (origin coordinates, scale factor, false easting/northing) were not accessible to the author: the NGS Beta site's own zone-definition and example-coordinate tables are served as interactive, JavaScript-rendered applications rather than as static or directly downloadable documents, and could not be retrieved in tabular form with the tools available for this monograph. Where a real numeric parameter set was available and independently verifiable (the current, pre-2022 SPCS 83 Kentucky Single Zone, via the EPSG Geodetic Parameter Registry), it is used below strictly as a documented *legacy* baseline, not as a stand-in for the unreleased 2022-generation parameters.

As a legacy reference point only, the current SPCS 83 Kentucky Single Zone (EPSG:3088/11630) is defined as a Lambert Conformal Conic (2SP) projection with false origin at latitude 36°20′ N, longitude 85°45′ W, standard parallels at 37°05′ N and 38°40′ N, and false easting/northing of 1,500,000 m / 1,000,000 m. This is the system the 2022-generation Kentucky zones, including `KYLDP7NC-2022`, are designed to replace or supplement; the comparison illustrates the parameter set involved, not the improvement achieved, which cannot be quantified without the unavailable 2022 parameters.

20.4 A fourth case: the participatory process itself, seen from the state side

The Wisconsin and Kentucky cases above show what a finished stakeholder-designed LDP layer looks like once published. Utah offers a documented view of the participatory process itself, in progress rather than finished. A work group formed from the Utah Department of Transportation, the Utah Council of Land Surveyors, the Utah Geospatial Resource Center (UGRC), and geomatics programs at Utah Valley University and Salt Lake Community College collaborated directly with NGS on the state's zone layout, responding to an NGS questionnaire with an explicit design preference: one statewide layer at an average ground elevation, plus a second layer of 15–25 low-distortion zones, each combining several counties with similar topographic relief and elevation. The preliminary layout that emerged from this process combined counties into 14 zones bounded by political (county-line) boundaries, rather than by purely geometric or distortion-optimal criteria.

Epistemic Notice

The Utah figures (14 preliminary zones, the 15–25 zone target range, the four named participating institutions) are drawn from a state government blog post describing a work-in-progress preliminary layout, not a finalized NGS zone-definition table; the final Utah SPCS2022 zone count and boundaries may differ from this preliminary proposal. It is reported here specifically as documentation of the participatory design *process* discussed throughout this chapter, not as a claim about Utah's final, adopted zone layout.

The choice to bound zones by county line rather than by a purely distortion-optimal geometric criterion is itself a real, documented instance of a trade-off this monograph's cartographic-theory framework treats abstractly: a jurisdictional boundary is administratively convenient (a surveyor or GIS analyst can identify their zone from a county map alone) at the cost of not being the distortion-minimizing boundary a purely mathematical optimization would produce. Ohio's 89-zone layer and Utah's proposed 14-zone layer sit at different points along the same coverage/distortion/administrative-simplicity trade-off surface, each shaped by what a different state's stakeholders judged to be an acceptable compromise.

20.5 What this adds to the theoretical picture

Taken together, the CONUS aggregate figures and the Ohio/North Carolina point-level comparison give the *No Map Is Best* series something the earlier, more theoretical chapters on SPCS2022 could not: a real, order-of-magnitude quantification of what participatory LDP design achieves in the field, expressed in the same parts-per-million units used throughout this monograph's treatment of classical map projections. The Ohio case in particular — a single real point, two real zone choices, a twenty-fold real difference in reported distortion — is as close as the modernized NSRS gets to a controlled experiment on the practical cost of the classical coverage/distortion trade-off.

Chapter 21

Tissot's Indicatrix and the Explicit Scale-Factor Field of a Low-Distortion Zone

21.1 From a combined scale factor to an explicit distortion field

Chapter 19 introduced the combined scale factor $k_{\text{combined}} = k_{\text{proj}} \times k_{\text{elev}}$ governing low-distortion projection zone (LDPZ) design, and gave the elevation factor $k_{\text{elev}} = R/(R + h)$ explicitly. It left the projection factor k_{proj} itself undeveloped, reporting only that LDPZ design chooses it so that k_{combined} stays within a few ppm of unity across the zone. This chapter supplies the missing piece: the explicit scale-factor field $k_{\text{proj}}(\varphi, \lambda)$ for the two conformal projections actually used by SPCS2022 — the Transverse Mercator (TM) and the Lambert Conformal Conic (LCC) — and shows algebraically why a narrow zone, well chosen, can hold k_{proj} to within a few ppm of a chosen reference value.

21.2 Why conformality collapses Tissot's indicatrix to a single number

For a general map projection, the local distortion at a point is captured by Tissot's indicatrix: the image, under the projection, of an infinitesimal circle on the reference ellipsoid, generally an ellipse with semi-axes a' (maximum scale) and b' (minimum scale) in orthogonal directions. A projection is conformal exactly when $a' = b'$ everywhere — the indicatrix degenerates to a circle at every point, of radius k, the single isotropic scale factor already used informally in Chapter 19. This is why SPCS2022, like its predecessors, restricts itself to conformal projections (TM and LCC): a single scalar field $k(\varphi, \lambda)$ suffices to describe distortion completely, with no separate accounting for angular distortion (zero, by conformality) or for the maximum-versus-minimum-scale gap that a non-conformal projection would additionally require.

21.3 The Lambert Conformal Conic scale factor, explicitly

For the spherical LCC with two standard parallels φ_1, φ_2, the standard construction (Snyder, 1987) introduces the cone constant

$$n = \frac{\ln(\cos\varphi_1 / \cos\varphi_2)}{\ln\!\left[\tan(\tfrac{\pi}{4} + \tfrac{\varphi_2}{2}) / \tan(\tfrac{\pi}{4} + \tfrac{\varphi_1}{2})\right]}, \qquad F = \frac{\cos\varphi_1 \, \tan^n(\tfrac{\pi}{4} + \tfrac{\varphi_1}{2})}{n},$$

and the radius, from the cone's apex, of the parallel at latitude φ:

$$\rho(\varphi) = R\,F\,\tan^{-n}\!\left(\frac{\pi}{4} + \frac{\varphi}{2}\right).$$

The scale factor along the parallel (and, by conformality, in every direction) at latitude φ is then

$$k_{\mathrm{LCC}}(\varphi) = \frac{n\,\rho(\varphi)}{R\cos\varphi}.$$

For a single-standard-parallel LCC design (setting $\varphi_1 = \varphi_2 = \varphi_0$, the common choice for a narrow zone centered on a reference parallel φ_0), this reduces to $k_{\mathrm{LCC}}(\varphi_0) = 1$ exactly at the standard parallel, with k_{LCC} departing from unity smoothly, and symmetrically to leading order, as φ moves away from φ_0 in either direction.

21.4 The Transverse Mercator scale factor, explicitly

For the spherical TM projection with central-meridian scale factor k_0, the scale factor at a point whose spherical distance from the central meridian corresponds to a plane offset x (in the projected coordinate system) admits, for x small relative to R — the regime of interest for any zone narrow enough to qualify as low-distortion — the standard second-order approximation

$$k_{\mathrm{TM}}(x) \approx k_0 \left(1 + \frac{x^2}{2R^2}\right).$$

Key Result

Both explicit formulas above share the same qualitative structure once linearized about their respective reference line (the central meridian for TM, the standard parallel for LCC): the scale factor departs from its reference value quadratically*, not linearly, in the distance from that reference line. This is the precise algebraic reason a narrow LDPZ can achieve few-ppm distortion where a wide statewide zone cannot: halving a zone's half-width away from its reference line reduces the projection-scale departure from unity by a factor of four, not two, so that modest reductions in zone width purchase disproportionate reductions in* $k_{\mathrm{proj}} - 1$.

21.5 Choosing k_0 below unity: trading a central deficit for edge relief

A design freedom left implicit in Chapter 19 is the choice of k_0 itself. Setting $k_0 = 1$ (scale exact on the central meridian or standard parallel) leaves the projection factor everywhere ≥ 1 away from the reference line, by the quadratic formulas above; choosing instead $k_0 < 1$ shifts the entire scale-factor field downward by a constant amount, trading a small scale *deficit* on the reference line itself for a corresponding reduction in the scale *excess* at the zone's edges. This is precisely the mechanism by which a LDPZ absorbs the elevation factor $k_{\mathrm{elev}} = R/(R+h)$, which is always ≤ 1 for $h > 0$: choosing k_0 to offset the zone's typical elevation-factor deficit brings the *combined* factor $k_{\mathrm{combined}} = k_{\mathrm{proj}} \times k_{\mathrm{elev}}$ close to unity across

the zone's full width and its typical elevation range simultaneously, rather than minimizing either factor in isolation.

Epistemic Notice

This chapter derives, from standard closed-form projection mathematics (Snyder, 1987, the standard USGS reference for map projection formulas, cited here as a classical mathematical source in the same manner Appendix A cites Heiskanen and Moritz), the algebraic mechanism underlying the LDPZ design logic already reported, at the level of design intent, in Chapter 19 and the state-level worked examples of Chapter 20. It reports no new empirical figures: the specific numerical choices of k_0, standard-parallel placement, and zone half-width for any actual SPCS2022 zone (including the Ohio, North Carolina, Kentucky, Utah, and Wisconsin cases already discussed in Chapter 20) remain exactly as sourced there, and this chapter does not attempt to recompute them independently from the closed-form expressions above — doing so would require the actual design parameters (standard parallels or central meridian, k_0, reference elevation) published for each zone individually, which is a separate exercise from establishing, as this chapter does, why the design method works in principle.

21.6 A closing link to the volume's own cartographic series

The quadratic-departure result derived above is a special case, restricted to conformal conic and cylindrical projections, of the general distortion-versus-coverage trade-off examined at greater generality (arbitrary projection families, not only conformal ones, and global rather than local coverage) in the *No Map Is Best* series' treatment of azimuthal projections and their Jensen-Shannon-divergence bounds. What SPCS2022's LDPZ mechanism demonstrates, in the narrow and highly practical setting of state and local coordinate systems, is the same principle the wider series argues at the scale of whole-world map projections: distortion is never eliminated, only relocated and rescaled by the choice of reference line and reference scale factor, with the quadratic falloff derived here setting the precise exchange rate between zone width and achievable precision.

Chapter 22

Michigan: A Statewide Layer Built on Legacy Geometry, and an LDP Layer Built by Tiling Counties

22.1 A fifth case, and a genuinely different design logic

Chapter 20 documented four state-level cases of SPCS2022 design in practice: the Ohio/North Carolina contrast in statewide-versus-dense-LDP philosophy, the Wisconsin and Kentucky naming and cross-reference conventions, and Utah's in-progress participatory process. Michigan, documented independently in the Michigan Society of Professional Surveyors' own 2022 Datum Committee reporting, adds a fifth case that differs from all four in one specific respect: its statewide zone is not a new NGS design at all, but an adaptation of a projection the state had already been using outside SPCS for decades, while its LDP layer was built by an explicit, geometrically motivated county-tiling rule rather than by county-line aggregation alone.

22.2 The statewide layer: absorbing the Michigan GeoRef system

Michigan's pre-existing statewide reference system, Michigan GeoRef, is an Oblique Mercator projection reportedly modeled on Ralph Moore Berry's Hotine Skew Orthomorphic formulation, used in the state independently of SPCS for years before the 2022 modernization. Rather than design a new statewide projection unrelated to this existing system, NGS designed the SPCS2022 statewide zone as an Oblique Mercator projection closely aligned with Michigan GeoRef itself.

Key Result

The MSPS committee reporting states plainly that one benefit of this alignment is that NGS will formally recognize and maintain the new oblique projection going forward, something it had not done for Michigan GeoRef up to that point; the state's own report also describes the NGS-designed statewide projection as showing distortions "significantly smaller" than those Michigan GeoRef users had previously encountered. This is a design pattern not documented elsewhere in this volume's other state cases: rather than replacing a legacy system with a new one, or defaulting to a scaled version of the existing SPCS 83 zones (Chapter 19's general default-design path), Michigan's statewide SPCS2022 zone absorbs and formally standardizes a projection the state had already been using on its own.

Epistemic Notice

The MSPS committee reporting used here (April 2020 newsletter, MSPS 2022 Datum Committee) is a state professional-society source describing NGS's own design work at the time of the report; it does not itself supply the Oblique Mercator's numeric defining parameters (Hotine Oblique Mercator central line azimuth, initial line longitude, or scale factor). Those parameters, if published on the NGS Alpha or Beta site as an interactive record in the manner already noted for Wisconsin and Kentucky in Chapter 20, were not accessible to the author in tabular form.

22.3 The LDP layer: an explicit county-tiling rule

For the second, low-distortion layer, the 2022 Datum Committee considered retaining Michigan's existing three-zone SPCS 83 configuration, but chose instead — after examining Wisconsin's and Indiana's LDP layers as precedents — to design a dedicated LDP layer for the state, retaining the Lambert Conformal Conic projection for every zone in that layer.

Key Result

The committee's own stated reason for keeping the Lambert projection specifically is geometric: distortion in an LCC zone accumulates north–south (away from the standard parallel or parallels), which permits the zone's east–west extent to be made correspondingly larger without exceeding the same distortion budget. Acting on this, the committee finalized a design rule of arranging counties into tiers of approximately two counties north–south by four counties east–west, restricting the east–west width specifically to keep the convergence angle bounded at the zone's extremities; the Upper Peninsula, with its different county size and shape, was handled as a documented exception to this tiling rule rather than by relaxing it.

The resulting proposed layer comprises seventeen named LDP zones, each identified by an anchor city and defined by an explicit county membership list published in the committee's own reporting: Ann Arbor (Jackson, Washtenaw, Wayne, Hillsdale, Lenawee, Monroe), Baraga (Ontonagon, Houghton, Baraga), Cheboygan (Emmet, Charlevoix, Cheboygan, Presque Isle), Delta (Dickinson, Menominee, Delta), Grand Rapids (Ottawa, Kent, Ionia, Clinton, Allegan, Barry, Eaton, Ingham), Iron (Gogebic, Iron), Kalamazoo (Van Buren, Kalamazoo, Calhoun, Berrien, Cass, St. Joseph, Branch), Keweenaw (Keweenaw, including Isle Royale), Marquette (Marquette, Alger, Schoolcraft), Mio (Otsego, Montmorency, Alpena, Crawford, Oscoda, Alcona), Newaygo (Oceana, Newaygo, Mecosta, Isabella, Muskegon, Montcalm, Gratiot), Oakland (Shiawassee, Genesee, Lapeer, St. Clair, Livingston, Oakland, Macomb), Pickford (Luce, Chippewa, Mackinac), Roscommon (Roscommon, Ogemaw, Iosco, Gladwin, Arenac), Saginaw (Midland, Bay, Huron, Saginaw, Tuscola, Sanilac), Traverse (Leelanau, Benzie, Grand Traverse, Kalkaska, Antrim), and Wexford (Manistee, Wexford, Missaukee, Mason, Lake, Osceola, Clare).

Epistemic Notice

This full county list is reproduced from the MSPS committee's own published proposal as of April 2020; the committee's report explicitly frames it as a proposal submitted to, and approved by, the Stakeholders Committee and then forwarded to NGS, with the numeric zone parameters (projection origin, scale factor, false easting/northing per zone) left to a subsequent phase of the committee's work, led by a named committee member, Jim Leitch, and not given in this source. Whether the final NGS-published SPCS2022 Michigan LDP layer matches this proposal exactly, or was subsequently modified during NGS review, is not established by this source and is not claimed here.

22.4 What Michigan's tiling rule adds to the theoretical picture

Chapter 21 derived, for the Lambert Conformal Conic in general, why scale departs *quadratically* rather than linearly from a chosen reference parallel — the exact algebraic reason a zone narrow in the direction of scale variation can hold distortion low while remaining wide in the orthogonal direction. Michigan's stated design rule is a direct, practitioner-level application of exactly this asymmetry: by keeping each LDP tier narrow north–south (the direction in which LCC scale factor varies) while allowing roughly twice the extent east–west (the direction in which, for a conic projection, scale is constant along a parallel), the committee's tiling method converts the quadratic-falloff result of Chapter 21 into a concrete, county-level zoning heuristic, arrived at independently by state-level stakeholders rather than derived from the projection mathematics by NGS or by this volume. The explicit secondary constraint — bounding the convergence angle at each zone's east–west extremities, a distortion of bearing rather than of scale, not treated by Chapter 21's scale-factor analysis — is a reminder that a real LDP design must jointly manage more than one geometric quantity at once, even when, as here, a single quantity (north–south scale variation) is allowed to dominate the layout logic.

Epistemic Notice

The connection drawn in this section, between Michigan's stated tiling rule and the quadratic scale-departure result of Chapter 21, is this volume's own interpretive link. The MSPS committee report states its geometric reasoning (accumulation of distortion north–south, and the resulting freedom to extend east–west) but does not itself invoke Tissot's indicatrix, the quadratic approximation, or any other formal projection-theory result; the correspondence is offered here as an observation about what the stakeholders' practical reasoning amounts to in the formal terms this volume has already established, not as a claim that the committee derived its rule from that mathematics.

Chapter 23

A Historical Precedent: The NAD 27 → NAD 83 Transition

23.1 What repeats, what is genuinely new

The transition currently underway is not the first in US geodetic history. The North American Datum of 1927 (NAD 27) was replaced by NAD 83 in 1986, in a project to readjust the entire North American geodetic network. It is useful, for anyone concerned with the history of cartography rather than only with contemporary geodesy, to isolate what structurally repeats in this new transition and what is instead genuinely unprecedented.

- **Repeats**: the need for a prolonged transition period, with dual support for both systems, and the consequent appearance — inevitable, and well documented also in the industry literature on the current transition — of "mixed-datum projects," in which part of the data remains in the old system and part in the new, with a risk of inconsistency if not managed with rigorous metadata.

- **Repeats**: the choice to maintain naming conventions that remain stable over time ("2022" in the name, not tied to the actual release year) for historical continuity, exactly as "NAD 83" and "NAVD 88" kept their own names even when actual release no longer coincided with the year indicated.

- **Genuinely new**: the availability of continental-scale satellite gravimetry (GRACE, GOCE) and airborne gravimetry (GRAV-D), which for the first time made possible a purely gravimetric vertical datum, rather than one founded on leveling. In 1986 this option did not technically exist.

- **Genuinely new**: the pervasiveness of civilian GNSS, which in 1986 was in its infancy (the GPS system had not yet reached full operational constellation), whereas today it constitutes the primary, universally assumed access infrastructure.

- **Genuinely new**: the explicit decomposition into four tectonically distinct reference frames (Chapter 2), made possible only by the centimeter-level resolution of plate rotations achieved through decades of continuous CORS observations.

23.2 A methodological lesson for the comparative analysis of datum transitions

Key Result

Todo resolved (July 2026 update). *A primary-source figure for the horizontal shift magnitude has since been traced: the NGS Beta SPCS2022 site (*Learn More about SPCS2022*, last updated June 2025) states directly that latitude and longitude in the 2022 terrestrial reference frames will differ from NAD 83 by roughly 1–2 meters in most areas, and by up to about 4 meters in some locations, driven mainly by NAD 83's non-geocentric origin (Chapter 1). An independent, peer-reviewed estimate for the Canada–US border specifically, published in* Geomatica *(Canadian Science Publishing), gives a horizontal coordinate difference of 1.3 to 1.5 meters between NAD83(CSRS) and NATRF2022 — consistent with, and falling inside, the NGS-stated national range.*

Epistemic Notice

Both figures describe the horizontal (latitude/longitude) shift only; neither source consulted disaggregates the estimate by state or region beyond the qualitative "some locations" near plate boundaries, and neither addresses the vertical (NAVD88→NAPGD2022) shift, for which Chapter 9 already provides the relevant bias/tilt figures (50 cm bias, 1 m tilt) from a distinct primary source. A fully region-disaggregated table is not among the sources consulted for this volume; the national-range and single-region figures reported above are accordingly the level of resolution at which this chapter's claim is made, not an interim figure standing in for a more precise one this edition lacks.

The most robust methodological lesson that can be drawn, even in the absence of that quantitative detail, is that every continental-scale datum transition follows a common structure independent of the technology available: a prolonged overlap period (here expected to conclude no earlier than the end of 2026), institutional communication punctuated by successive formal announcements (here via Federal Register Notice, see Chapter 24), and finally a consolidation phase in which the legacy system remains accessible but no longer updatable.

Part V

Institutional Framework and Verified Chronology

Chapter 24

Official Chronology of the Project

24.1 The origins (2007–2017)

- **2007** — NGS acquires its first airborne gravimeter and launches the GRAV-D project.

- **2008** — Publication of the 2008–2018 Ten-Year Plan, which formalizes for the first time the goal of replacing NAVD 88 with a gravimetric vertical datum.

- **2013** — Revision of the strategic plan: the target date for the release of the modernization is set at 2022.

- **2017** — Naming agreement reached with Canada and Mexico to include "2022" in the names of the modernized system's components.

24.2 The delay and the new planning (2017–2024)

Starting in 2017, operational problems mainly related to staff recruitment and retention, along with the failure to meet some GRAV-D data-collection targets, led NGS to reassess the feasibility of a 2022 release. Blueprint Part 2 (2021 revised edition) explicitly records this delay, while nonetheless retaining the "2022" naming convention for communicative continuity and to avoid confusion, following the same pattern already seen with the releases of NAD 83 (1986) and NAVD 88 (1991), which were themselves not free of discrepancies between name and actual release year.

24.3 The 2024 Federal Register Notice and the staggered release

Key Result

On October 9, 2024, NGS published a Federal Register Notice formally updating the implementation timeline for the modernized system, establishing the following milestones, also confirmed by the official NGS FAQs:

1. *Staggered release of the modernized system's components for public testing on* `beta.ngs.noaa.gov`*, during 2024–2026, with at least six months of testing following the release of the last component.*
2. *Throughout the entire testing period, the current system (NAD 83, NAVD 88) remains the sole official system.*
3. *Integration of ITRF2020 into the current system's products, planned for late 2024/early 2025.*
4. *Approval vote by the Federal Geodetic Control Subcommittee (FGCS), expected in mid-2026.*
5. *In the event of a favorable vote, publication of a second Federal Register Notice and the start of a several-month transition process toward official system status.*

24.4 The January 13, 2027 deadline

A figure of particular practical relevance, confirmed in the updated official NGS FAQs: the final deadline for submitting geodetic survey projects (GPS and differential leveling projects) aimed at creating or updating geodetic control within the current system is set at **January 13, 2027**. After that date, the legacy tools (OPUS Projects 5, WinDesc, Translev) will remain available for reference until the modernized system is fully implemented, but new submissions within the current system will no longer be accepted. NGS has specified that, in the six months preceding the deadline, it will nonetheless continue to review and approve project proposals, while retaining the right to reject proposals deemed unachievable by the deadline.

Epistemic Notice

This chronology is verified against primary NGS sources consulted in July 2026 and reflects the state of the project as of that date. The schedule itself has, by NGS's own admission, already slipped more than once (from the original 2018, to 2022, to the current 2025–2026 window): the reader is invited to treat every date given here as the best estimate available at the time of writing, not as a binding commitment on the agency's part.

24.5 Update from Geo Week 2026: the vote slips again

At Geo Week 2026 (Denver, February 17–18, 2026), NGS presented an updated version of the timeline described above. According to the slides presented by Seth Pollack and reported by David Zilkoski in *GPS World*, the FGCS approval vote — previously described in NGS's own FAQs as "likely in mid 2026" — is now anticipated in **late 2026 or early 2027**, with full official adoption and transition to the modernized system, following FGCS approval and Federal Geographic Data Committee (FGDC) endorsement, potentially extending into the first part of 2027.

Key Result

This is a further, real-time instance of the same slippage pattern already noted above for the project's earlier milestones (2018 → 2022 → 2025/2026): the vote originally targeted for "mid 2026" had, by the time of this monograph's writing (July 2026), already publicly slipped to a "late 2026 or early 2027" window — confirmed directly by NGS presenters rather than inferred, and consistent with the general observation that every date in this chronology should be read as the best current estimate rather than a fixed commitment.

At the same conference, NGS also announced an institutional detail unrelated to the technical timeline but illustrative of the project's multi-decade human dimension: NOAA's Table Mountain Gravity Observatory in Boulder, Colorado, long used for absolute gravity work supporting the geoid modeling described in Chapter 6, was renamed the J. P. Blackwell Gravity Observatory, honoring Juliana Blackwell, NGS's retired Director, for her leadership of the agency during the years in which GRAV-D, GEOID2022, and the wider modernization effort were developed.

Chapter 25

The Geospatial Data Act and the Regulatory Dimension

25.1 A legal obligation, not just a technical recommendation

Unlike many technological transitions in cartography discussed elsewhere in this volume and in the *No Map Is Best* series as primarily scientific or design choices, the adoption of the new reference frames by US federal agencies is not optional. The Geospatial Data Act of 2018 (a federal law that partly redefined, without fully replacing, the earlier OMB Circular A-16), in its Section 2809, requires that all federal civilian agencies that collect, produce, acquire, maintain, or disseminate geospatial data must use the new reference frames within five years of their official adoption by the Federal Geodetic Control Subcommittee (FGCS) as part of the NSRS.

25.2 Institutional architecture: from a budget circular to federal statute

The Geospatial Data Act did not create federal geospatial governance *ex nihilo*; it codified into law, and in some respects extended, a policy apparatus that had previously rested on executive rather than legislative authority. The Federal Geographic Data Committee (FGDC), the interagency body responsible for coordinating federal geospatial policy, had existed since 1990 under Office of Management and Budget (OMB) Circular A-16, and was subsequently strengthened by Executive Order 12906 (1994), which tasked it with coordinating development of a National Spatial Data Infrastructure (NSDI). The GDA, enacted October 5, 2018 as Subtitle F of the FAA Reauthorization Act of 2018 (P.L. 115–254) and now codified at 43 U.S.C. §§ 2801–2811, places the FGDC on a statutory footing for the first time, chaired by the Secretary of the Interior with the OMB Director as Vice Chair, and gives it explicit authority to designate National Geospatial Data Asset (NGDA) data themes and to oversee their coordinated management.

Epistemic Notice

It is worth being precise about what changed and what did not: the GDA *continues* the FGDC and the NSDI concept rather than replacing them outright, but it converts what had been discretionary executive-branch policy (Circular A-16, EO 12906) into binding statutory obligations subject to congressional oversight, inspector-general audit, and — as discussed below — a hard funding restriction. This distinction between continuity of institutions and change in their legal force is easy to lose in secondary summaries of the Act.

25.3 Geodetic Control as a National Geospatial Data Asset theme

Among the data themes the FGDC designates under the GDA are the seven original NSDI Framework Data Themes inherited from the pre-statutory NSDI effort: Geodetic Control, Elevation, Hydrography, Cadastral, Orthoimagery, Transportation, and Government Units. The presence of *Geodetic Control* on this list is what gives Section 2809 (formerly H.R. 302 § 759A, "Limitation on Use of Federal Funds") its direct bearing on the NSRS modernization discussed throughout this volume: once NGDA standards for the Geodetic Control theme are established, covered agencies face a statutory deadline — the "implementation date," defined as five years after those standards are set — after which federal funds may no longer be used to collect, produce, acquire, maintain, or disseminate geospatial data that fails to comply with them.

Epistemic Notice

A methodological nuance worth flagging explicitly, since it is often collapsed in secondary and even official summaries: the statutory text of Section 2809 is written generically, in terms of compliance with whatever standards the FGDC establishes for a given NGDA theme, and does not itself name NATRF2022, NAPGD2022, or the Federal Geodetic Control Subcommittee (FGCS). The specific reading given in Chapter 25's opening section — that federal civilian agencies will be required to use the new reference frames within five years of FGDC adoption as part of the NSRS — is the interpretation stated explicitly by NGS itself in its official FAQs, not an inference drawn independently in this volume; it is reported here as an authoritative agency reading of the statute's application to this specific case, distinct from the bare statutory text.

25.4 A statute with teeth, but unevenly enforced so far

Whether Section 2809's funding restriction functions as an effective compliance mechanism is, in part, an empirical question, and the early evidence — concerning GDA compliance in general, not the geodetic-control theme specifically, since the relevant implementation date for that theme lies in the future — is mixed. Statutorily, GDA Section 2808 (§ 759 in the original H.R. 302 numbering) enumerates thirteen "covered agency responsibilities," and Section 2808(b) requires each covered agency's inspector general to audit compliance no less than once every two years. Audits published under this requirement have found substantial gaps: a 2020 audit found that the Department of Health and Human Services had made only partial progress toward GDA compliance, having neither completed a department-wide inventory of its geospatial data assets nor designated a required senior agency official for geospatial information; separate audits by the General Services Administration's Office of Inspector General, in 2023 and again in a 2024 follow-up, found that GSA was not fully complying with the Act, citing both incomplete integration of geospatial data into its compliance reporting and quality deficiencies (including inaccurate coordinates) in the datasets it had reported.

Epistemic Notice

These findings concern general-purpose federal geospatial data governance under the GDA as a whole, not compliance with the geodetic-control theme specifically, whose five-year funding-restriction clock has not yet started in earnest. They are reported here as context for assessing the credibility of the FAQ's own five-year compliance timeline: an oversight mechanism that multiple inspectors general have already found only partially effective for the Act's general provisions is not guaranteed to produce smooth, on-schedule federal-wide migration to the new reference frames once the Geodetic Control theme's own implementation date arrives. This is an assessment of institutional track record as documented through July 2026, not a prediction about the geodetic-control case specifically — that case has not yet occurred, and this volume, being a synchronic account, offers no forecast of its outcome, only the institutional record available to inform one.

25.5 A more mixed picture in the most recent audit cycle

Key Result

Update (audit cycle 2024–2026). *The GSA and HHS findings cited above are not representative of every covered agency's track record. The Department of Transportation's Inspector General, in an October 2024 report, found DOT had made significant progress toward GDA compliance, though it had not maintained an accurate geospatial-data inventory; a further DOT OIG audit of fiscal-year-2026 compliance was formally initiated in February 2026, continuing the statutory two-year audit cycle. Separately, the Department of Labor's Inspector General reported in an October 2024 audit that DOL "continues to make progress" toward GDA compliance. At the high end, at least one covered department's inspector general has reported full or near-full compliance with the Act's thirteen covered-agency responsibilities in a recent cycle.*

Epistemic Notice

This more recent evidence complicates, without overturning, the "unevenly enforced" framing above: the GDA's biennial inspector-general audit mechanism does appear to be functioning as a genuine forcing function over successive cycles, with several agencies reporting continued or renewed progress rather than static non-compliance. Whether this constitutes a durable trend toward full compliance across all covered agencies by the time the Geodetic Control theme's own five-year funding-restriction clock starts running — as opposed to a cycle in which some agencies improve while others (as with the GSA case, itself already a follow-up to an earlier finding) persist in the same gaps — cannot be settled from the sources consulted here, and remains the empirical question this chapter identified above.

25.6 Beyond the federal level

The obligation extends, in conditional form, beyond federal agencies alone: any state agency or organization that receives federal funding to generate or process geospatial data must conform to the modernized system. For entities that fall into neither of the two preceding categories — neither a federal agency, nor a recipient of federal funds for geospatial activities — use of the new system remains governed by applicable state or local law, or by specific contractual terms, with no direct federal obligation.

Epistemic Notice

Some states may require a legislative amendment in order to formally use the new reference frames in their cadastral and administrative acts. A collaborative committee with representatives from the National Society of Professional Surveyors (NSPS), the American Association for Geodetic Surveying (AAGS), and NGS has developed model legislative text, designed as an amendment to existing state laws, which uses generic wording ("most recent datum," "NGS or its successors") precisely to avoid the need for further legislative amendments upon future version updates. According to the sources consulted, examples of eleven new state statutes have already been made available by NGS as a model for other states.

25.7 Why this chapter closes the volume

If the preceding chapters treated NSRS modernization as a scientific and cartographic problem — distortion theory, gravimetry, coordinate transformation — this final chapter recalls its dual nature: a modern geodetic datum is not merely a more accurate mathematical model than its predecessor, but also a legal-administrative artifact, whose actual adoption depends on an interplay of federal regulation, conditional funding, and state legislation. This is a dimension that historical cartography, typically dealing with datums that are by now settled and uncontested, tends to take for granted; observing it while still taking shape — as has been possible in this volume, written during the transition window itself — offers a rare vantage point on how a shared geodetic reference is, quite literally, negotiated and enacted before becoming invisible everyday infrastructure.

Chapter 26

Monuments, Coordinates, and the Law: Why a Datum Change Does Not Move a Fence

26.1 A concrete point of confusion

Chapter 25 established that the modernized NSRS carries statutory weight for federal agencies. A related but distinct question, of much more immediate concern to individual landowners, farmers, and local surveyors, is whether the numerical shift in coordinates that accompanies the transition to NATRF2022 and NAPGD2022 changes where property boundaries actually are. Agricultural trade press covering the 2026 rollout has reported concrete cases illustrating the confusion this can generate: a grower using an RTK base station tied to NAD 83 to guide automated field equipment along a boundary with sub-inch precision may find that, once the same coordinates are recomputed in NATRF2022, the guidance line appears to have shifted by several feet relative to the neighboring parcel — prompting the natural but mistaken inference that the fence, or the boundary itself, has moved.

Epistemic Notice

The fence has not moved. What has moved is the *numerical coordinate* historically used to describe its location, and only because the reference frame those numbers are expressed in has itself been redefined. This is precisely the distinction this chapter exists to make explicit, since — as the source reporting the Iowa case notes independently — correcting the mapped data, not the fence, is the required remedy.

26.2 The doctrinal principle: monuments control, not coordinates

United States boundary law, developed principally around the retracement of the Public Land Survey System (PLSS) but applicable by extension to metes-and-bounds and other survey systems, rests on a hierarchy of evidence in which physical and record monumentation take precedence over any subsequently computed numerical position. The Bureau of Land Management's own Manual of Surveying Instructions states the principle in stark terms: the boundaries and subdivisions of the public lands, once surveyed under approved instructions, are "unchangeable after the passing of the title by the United States," with the physical evidence of the original survey — monuments established on the ground, and the field notes and plats recording them — controlling over any later remeasurement, however more precise.

The underlying statutory basis traces back to the Land Act of February 11, 1805, which established that original lines and corners in the public-land states are unalterable by a retracing surveyor; as one standard treatise on boundary law puts it, not even a court may relocate a section corner once established, regardless of how imprecisely it was originally located.

Key Result

A datum redefinition changes the numbers *that describe where monuments are, not the legal weight of the monuments themselves. A fence, a section corner, or a recorded metes-and-bounds description tied to physical or documentary evidence continues to control the boundary after NATRF2022 and NAPGD2022 become official, exactly as it did under NAD 83 and NAVD 88 before the transition.*

26.3 The evidentiary hierarchy in practice

Professional and judicial treatment of boundary retracement consistently places natural and artificial monuments above courses, distances, and — lowest in the hierarchy when a monument or an unambiguous record trail exists — computed coordinates. Case law such as *Rogers v. Taylor*, 45 S.W.2d 322 (Tex. App. 1932), is cited in the professional continuing-education literature as an instance of a court preferring the original surveyor's field notes and monument calls over a later survey that attempted to redefine the boundary from measurements alone. A frequently quoted formulation of the underlying rule — attributed in retrospective commentary to surveyor Curt Brown, writing in 1968 — holds that "the original position of a monument, if called for, is unalterable except by reconveyance," a rule of law rather than a mere surveying convention, and one that predates satellite positioning entirely.

Epistemic Notice

The case-law and treatise citations in this section are drawn from professional surveying-education literature (continuing-education course materials, trade-press retrospectives, and a standard boundary-law textbook), not from this volume's own independent verification of primary court records or the full text of the 1805 Land Act. They are reported at the same reliability tier as the industry sources used elsewhere in this volume — useful for establishing the shape and consensus of professional practice, but a reader with a live boundary dispute should consult primary legal sources or a licensed surveyor/attorney directly, not this chapter.

26.4 Where coordinates do carry evidentiary weight

None of the above should be read as saying coordinates are legally irrelevant. Professional literature on the subject — notably a widely cited analysis of coordinates as boundary evidence — observes that courts have accepted coordinates as the best available evidence for restoring a *lost* corner, precisely in cases where no adequate monument or record trail survives; the same literature stresses, however, that this acceptance is conditional on the surveyor properly documenting the datum and epoch of the coordinates presented, since an undated, un-epoched coordinate is not a well-defined position at all once a time-dependent reference frame is in use. This is exactly the discipline introduced, from the geodetic rather than legal side, in Chapter 12's discussion of survey-epoch and reference-epoch coordinates: a coordinate without an epoch is analogous, in this chapter's terms, to a monument call without a date, and both are weaker evidence than their properly qualified counterparts.

Key Result

The datum modernization discussed throughout this volume makes epoch-and-datum documentation more *important for any coordinate offered as boundary evidence, not less: as the number of reference frames in concurrent legal and practical use increases (NAD 83, NATRF2022, and their various realizations), an unlabeled coordinate becomes correspondingly more ambiguous as evidence, reinforcing rather than undermining the traditional primacy of physical and record monumentation.*

26.5 An acknowledged exception: genuine land movement

The doctrine of monument permanence is not absolute. Boundary-law commentary recognizes a narrow exception for gradual, genuine movement of the land itself — as opposed to a mere redefinition of the coordinate system describing it — citing, for instance, the continual northward creep of land southwest of the San Andreas Fault in coastal California, or subsidence from subsurface fluid withdrawal, as cases where ownership lines have, in some jurisdictions and circumstances, been held to move with the physical shift of surface monuments and improvements themselves.

Epistemic Notice

This exception is conceptually distinct from, and should not be confused with, the intra-frame velocities and glacial isostatic adjustment (GIA) signals discussed in Chapters 3, 10, and 16. Those chapters describe geodetic *models* of crustal motion, built to keep coordinates numerically consistent with a moving physical reality over time; whether, and under what legal doctrine, a given jurisdiction actually treats a boundary as moving with such physical motion is a separate question of property law, on which this volume, being a work of geodesy and cartographic-distortion history rather than a legal treatise, takes no position beyond noting that the question exists and has already been litigated in at least the land-subsidence and fault-creep contexts cited above.

26.6 Closing the loop with the regulatory chapter

Read together with Chapter 25, this chapter completes a picture in which the modernized NSRS operates on two distinct legal registers simultaneously: a statutory register, in which the Geospatial Data Act binds federal agencies to eventually adopt the new frames for their own data holdings, and a much older common-law and public-land-survey register, in which the physical and documentary evidence of where a boundary actually runs is, and remains, largely indifferent to which geodetic reference frame is fashionable in a given decade. The practical lesson for anyone affected by the transition — echoed independently by the agricultural-press guidance cited at the opening of this chapter — is to update the *data* (GNSS base-station configurations, GIS layers, guidance-line files) rather than to infer that the *land* has changed.

Chapter 27

Practical Impacts: Flood Risk Maps and National Elevation Models

27.1 When a datum change directly touches people's lives

The preceding chapters have treated modernization mainly as a problem of geodetic theory and infrastructure. This chapter, shorter than the others, focuses on two derived products whose practical impact is immediate and tangible for the non-specialist public: the flood risk maps of the Federal Emergency Management Agency (FEMA) and the national elevation model of the U.S. Geological Survey.

27.2 Flood risk maps (DFIRM)

The Digital Flood Insurance Rate Maps (DFIRM), produced by FEMA, determine — among other things — flood insurance premiums for millions of US properties, based on ground elevation relative to the expected flood level. Since that elevation is, by definition, an orthometric height referred to a vertical datum, a change in vertical datum can, in principle, move a property in or out of an insurance risk zone simply as a result of redefining the reference surface, not because of any physical change in the terrain.

NGS conducted, as early as 2010, a joint pilot project with FEMA to determine the expected impact of the new geopotential datum on floodplain mapping, focused on North Carolina. Blueprint Part 2 refers to the full report of that pilot project for technical details, noting that coordination between NGS and FEMA — through the Federal Geodetic Control Subcommittee and its working groups — would continue and intensify as the actual release of the modernized system approached.

Epistemic Notice

The sources consulted for this volume contain no public update, subsequent to the 2010 pilot project, quantifying the expected nationwide impact on DFIRM maps. Given the direct implications for insurance premiums and cadastral disputes, this absence is itself a substantive finding of this chapter, not merely a gap awaiting a future source: it indicates that, as of the transition's own approach in 2026, the derived third-party impact of the vertical datum change on flood-insurance mapping had not been quantified in any document available to this volume, fifteen years after the pilot project that was meant to anticipate it.

27.3 The USGS 3D Elevation Program (3DEP)

The second derived product of practical relevance is the U.S. Geological Survey's 3D Elevation Program (3DEP), the national high-resolution LiDAR data collection program that today forms the basis of most digital elevation models (DEMs) used at the federal, state, and private levels in the United States. Blueprint Part 2 confirms that NGS maintains regular communication with USGS regarding 3DEP, with the explicit expectation that this coordination will intensify as the release of the modernized system approaches — precisely because every existing DEM, being expressed in NAVD 88, will require a conversion or re-referencing strategy to NAPGD2022 in order to remain usable consistently with the new system.

27.4 3DEP in numbers: coverage, funding, and the next-generation program

Chapter 27 has so far treated 3DEP mostly qualitatively, as "the national LiDAR program." It is worth being more concrete about its scale and trajectory, both because these figures give a sense of the sheer volume of downstream elevation data that will eventually need to be re-referenced to NAPGD2022, and because 3DEP's own progress is itself an illustration of how long a "national baseline" infrastructure project realistically takes to complete. USGS reported that baseline LiDAR data acquisition had reached 89% of national coverage by the end of 2022, funded through a partnership structure combining USGS appropriations, other federal agency contributions, state and local cost-share, and — since fiscal year 2023 — supplemental Inflation Reduction Act funding; USGS's stated target is to complete a national 3DEP baseline map by 2027, a timeline that places final national LiDAR coverage roughly contemporaneous with, but not necessarily coordinated to, the modernized NSRS's own 2026 release.

Epistemic Notice

The 89% figure and the 2027 completion target both describe the LiDAR *baseline acquisition* program, not its re-referencing to NAPGD2022. Nothing in the sources consulted for this volume indicates that 3DEP data collected under NAVD 88 will be automatically or immediately converted upon the modernized NSRS's release; Chapter 27's original observation — that every existing NAVD 88-referenced DEM will require a conversion or re-referencing strategy — therefore applies to a growing, near-complete national archive, not a small legacy dataset.

A separate but closely related data point, useful for calibrating the economic stakes of elevation-data quality broadly (though not a direct estimate of the datum transition's own impact, a distinction worth holding onto given this chapter's no-invented-data discipline), comes from the 3D Nation Elevation Requirements and Benefits Study, a joint NOAA/USGS study conducted by the firm Dewberry and published in September 2022. Drawing on structured input from 45 federal agencies, 56 states and territories, and 58 non-governmental organizations, the study estimated that a fully implemented national elevation and bathymetry program — meeting all identified requirements, a scenario broader than 3DEP's current baseline scope — could generate on the order of $13.5 billion in benefits annually across resource management, hazard mitigation, and infrastructure applications. NGS's own successor initiative, the 3D National Topography Model (3DNTM), launched to integrate 3DEP elevation data with USGS hydrography products, explicitly builds on this study's findings and continued into active data-collaboration announcements for fiscal years 2025 and 2026.

Epistemic Notice

As with the DFIRM impact figures discussed above, the $13.5 billion estimate is a benefits projection for a hypothetical fully-implemented elevation program, not a measured or projected consequence of the specific NAVD 88 → NAPGD2022 vertical datum transition. Citing it here risks conflating two related but analytically distinct questions — "what is the economic value of better elevation data in general" versus "what does changing the reference datum of existing elevation data cost or save" — and the reader should keep that distinction in mind; it is reported for context on the broader stakes of elevation-data infrastructure, not as a quantification of the transition discussed in this chapter.

27.5 The 3DEP baseline: completed, ahead of the 2027 target

Key Result

Update (Geo Week 2026). *The §89%/2027 figures given above describe the state of the program as of late 2022–2023. At Geo Week 2026, USGS announced that baseline data acquisition for 3DEP is now complete: the program has accumulated 76 trillion lidar points of national coverage, reaching the goal originally targeted for 2027 ahead of schedule. USGS's own 3DEP Broad Agency Announcement FAQ, and its FY26 Data Collaboration Announcement, confirm the same completion estimate for 2026 and describe the program's focus shifting from initial baseline acquisition to next-generation refresh coverage (for areas where baseline data have become five years old, or eight in Alaska, Hawaii, and the territories) under the broader 3D National Topography Model (3DNTM) initiative.*

Epistemic Notice

This resolves the acquisition-timeline half of this chapter's earlier flag, but not the re-referencing question the chapter raised alongside it: completion of the national lidar baseline is a statement about coverage, not about which vertical datum any given tile is expressed in. Nothing in the sources consulted for this update states that the newly completed 3DEP baseline, largely collected and published against NAVD 88, has itself been re-referenced to NAPGD2022; the re-referencing strategy this chapter originally identified as still needed therefore applies, if anything, to a now-complete rather than a still-growing national archive.

27.6 FEMA readiness: still an open question, now voiced in the trade press

The informational gap this chapter originally flagged — no public update, since the 2010 North Carolina pilot, quantifying NAPGD2022's expected nationwide impact on DFIRM maps — remains unfilled by any NGS or FEMA technical report identified for this edition. It has, however, become a subject of explicit trade-press concern as the 2026 rollout has approached. A May 2026 column in *The American Surveyor* raised the readiness question in blunt terms, noting that municipalities largely lack budget to do more than apply a simple conversion factor to their benchmarks, and openly doubting whether FEMA could realistically republish a nationwide set of updated flood-insurance-rate-map panels promptly once the new datums become official; the same piece illustrates, with a composite example, the kind of ad hoc conversion-factor memoranda some localities may be left to rely on in the interim.

Epistemic Notice

A trade-press opinion column is not a substitute for the quantitative nationwide impact assessment this chapter has been asking for since its original drafting, and it is reported here as evidence of professional concern about the transition's practical readiness, not as data about the transition's actual effect. It does, however, corroborate — from outside NGS's own documentation — this chapter's core observation: that the derived, third-party impacts of the vertical datum change remain comparatively under-documented relative to the geodetic core of the modernization discussed in the rest of this volume, even as the FGCS vote itself (Chapter 13) approaches.

27.7 A closing methodological remark

This chapter, shorter and more open-ended than the others, honestly reflects the state of publicly available documentation: while the purely geodetic aspects of the modernization (Chapters 1–10) are documented by NGS in great quantitative detail, the derived impacts on third-party products such as DFIRM and 3DEP remain, as of the time of writing, described only qualitatively in the primary sources consulted. This is a case where the no-invented-data discipline adopted throughout this volume requires explicitly flagging an informational gap, rather than filling it with plausible but unverified estimates.

Chapter 28

A Trilateral Project: Coordination with Canada and Mexico

28.1 Beyond national borders

A thread that has surfaced repeatedly in the preceding chapters — the 2017 naming agreement (Chapter 24), the joint production of GEOID2022 (Chapter 8), the empirical agreement on the value W_0 through the comparison of nearly two hundred tide gauges in the US and Canada (Chapter 7) — deserves to be gathered into a chapter of its own, because it reveals a dimension of the project easily lost if the modernization is viewed solely from the US standpoint: NSRS modernization is not a single country's isolated project, but the result of explicit trilateral coordination among the United States, Canada, and Mexico.

28.2 The Canadian Geodetic Survey

The Canadian Geodetic Survey (CGS) appears as co-author or partner at several key points in the documentation consulted: the agreement on the name "2022" for the system's components (2017); the joint decision on the value $W_0 = 62,636,856.0$ m^2s^{-2}, adopted jointly by NGS and CGS after independent analysis of tide-gauge data; the joint adoption of the future datum-replacement threshold, set at a discrepancy of 2 m^2/s^2 relative to GMSL (Chapter 9); and equal participation in the production of GEOID2022. On the geometric side, it should also be noted — based on the industry sources consulted (Trimble Positioning Services) — that Canada will replace its current NAD83(CSRS) datum with NATRF2022, while retaining, for heights, a new version of its own national vertical datum, the Canadian Geodetic Vertical Datum of 2013 (CGVD2013 v1), rather than adopting NAPGD2022 directly for heights.

Key Result

Todo substantially resolved (July 2026 update). *A CGS-authored conference presentation (Donahue et al., FIG Working Week 2023) corroborates and refines the Trimble account: Canada will not adopt the NAPGD2022 name for heights, but will release an updated realization,* ***CGVD2013(SGEOID2022)****, sharing the* same defining W_0 value *as NAPGD2022 (62,636,856.0 m^2s^{-2}) and built from the jointly produced GEOID2022 model. In other words, the retention of the CGVD2013 name is a matter of naming continuity for Canadian users, not a divergence in the underlying geopotential definition — the two vertical datums are, by design, the same physical surface under two national labels.*

Epistemic Notice

This remains short of a full primary-source confirmation from Natural Resources Canada's own web documentation, which as of the sources consulted describes CSRS modernization in general terms without repeating the exact realization name found in the conference paper. The conference paper, authored and presented by Canadian Geodetic Survey staff, is treated here as a strong quasi-primary source; this volume reports the CGVD2013(SGEOID2022) realization name at that level of corroboration, distinct from a direct citation in NRCan's own published documentation, as the state of the evidence through July 2026.

28.3 Mexico's Instituto Nacional de Estadística y Geografía (INEGI)

Mexico's role, although less extensively documented in the sources originally consulted for this chapter than Canada's, appears explicitly in Blueprint Part 2 regarding the production of GEOID2022: the final model will be a joint product of three agencies — NGS, CGS, and INEGI — with the declared goal of a single shared model for the entire modernized North American continent, thereby avoiding the geodetic fragmentation at national borders that had characterized, to varying degrees, the era of national hybrid geoids discussed in Chapter 6.

Key Result

Todo substantially resolved. *A 2026 peer-reviewed paper on* xGGM23, an Updated Geoid Model for Mexico*, published in the IAG Symposia series, clarifies the Mexican side of this trilateral picture: alongside its participation in the jointly produced GEOID2022, Mexico maintains its own separate, nationally validated gravimetric geoid model. The current official model, GGM10, is rated by INEGI (2015) at roughly 20 cm accuracy, judged sufficient for sub-meter mapping applications; the 2026 paper's own independent assessment puts GGM10's accuracy closer to 25 cm. The newer experimental model, xGGM23, is reported to achieve better than 10 cm accuracy, explicitly aimed at emerging high-precision applications — robotic total-station and LiDAR surveys, drone photogrammetry — that GGM10 was never designed to support.*

The methodological detail that ties this most directly to material already presented in this monograph is the paper's own validation strategy: xGGM23 was assessed against three independent GNSS/leveling datasets, one of them Mexico's own national leveling network (fully processed against NAVD 88 in 2015), and the other two the very same GSVS11 (Texas) and GSVS17 (Colorado) calibration lines already discussed as GRAV-D's own validation campaigns in Chapter 6. In other words, the two GSVS lines this monograph already used to quantify GRAV-D's benefit for GEOID2022 are, independently, part of the international validation baseline for Mexico's own national geoid effort — a direct empirical link, rather than a merely institutional one, between the US and Mexican geoid programs.

Epistemic Notice

GGM10/xGGM23 is Mexico's own *national* vertical reference product, distinct from GEOID2022 in the same sense that Canada's CGVD2013(SGEOID2022) (below) is distinct from GEOID2022 while sharing its underlying W_0 value and gravimetric input: the pattern of a jointly produced continental geoid coexisting with nationally branded, nationally validated vertical realizations recurs on both the Canadian and Mexican sides of the trilateral effort, though the degree of technical integration between the national product and GEOID2022 itself was not established for Mexico with the same clarity as for Canada from the sources consulted here.

28.4 Why the trilateral dimension matters for distortion theory

Key Result

An aspect often invisible to those who think about cartographic distortion only in terms of a single projection or a single national datum: geodetic consistency across political borders is not an automatic byproduct of good science, but requires explicit and ongoing institutional agreement. A geoid built independently by three national agencies, however technically excellent each one is, would almost certainly produce residual discontinuities along the US-Canada and US-Mexico borders — a special case, at geodetic scale, of the same "stitching" problem between the validity domains of local projections discussed in connection with the low-distortion SPCS2022 zones (Chapter 19). The choice of a single shared model, rather than three nationally harmonized after the fact, is the structurally more robust solution to this problem, and is for this reason of direct interest to cartographic distortion theory as applied to multi-national reference systems.

Chapter 29

Preparing the Profession: Software Readiness, the Retirement of a Unit, and the New Metadata Discipline

29.1 A transition that arrives through software, not through decree

The preceding chapters in this part of the volume have examined how the modernized NSRS touches property law (Chapter 26), federally derived elevation products (Chapter 27), and international coordination (Chapter 28). For the working surveyor, engineer, or GIS analyst, however, the transition will not arrive as an abstract redefinition of reference frames: it will arrive as a software update, a settings dialog, and a set of metadata fields that either get filled in correctly or do not. This chapter examines that more mundane, but practically decisive, layer of the modernization.

29.2 Vendor readiness: a distributed, uneven process

NGS does not control the commercial software stack through which the overwhelming majority of practitioners actually touch coordinates. Industry commentary consistently frames vendor support as a distributed process to be tracked rather than a single event to await. Esri has publicly confirmed that its ArcGIS technology already distinguishes between the two competing definitions of the foot discussed below, and is coordinating directly with NGS on the rollout. Firms tracking the transition for their own operational planning report an active, ongoing verification exercise across the wider commercial-off-the-shelf (COTS) landscape — Esri ArcGIS, Autodesk products, Global Mapper, and TerraSolid among them — precisely because, as one such firm puts it, no organization wants half its data in one datum and half in another.

Epistemic Notice

No source consulted for this volume provides a single, authoritative, cross-vendor readiness matrix (i.e., a table stating exactly which version of each major COTS package supports NATRF2022/NAPGD2022 natively, and from what date). What is corroborated is the qualitative pattern: major vendors are engaging with NGS ahead of the rollout, and firms serving the surveying/GIS sector are treating vendor verification as their own responsibility rather than something they can assume has already happened. A practitioner planning an actual migration should verify current support status directly against release notes for the specific software in use, not against this chapter.

29.3 The quiet retirement of the US survey foot

A change that predates the main NATRF2022/NAPGD2022 rollout, but is functionally inseparable from it, concerns the unit in which many American coordinates are still expressed. Since 1959, the United States had maintained two legally distinct definitions of the foot side by side: the international foot, defined as exactly 0.3048 m, used for ordinary commerce and engineering; and the U.S. survey foot, defined as exactly 1200/3937 m ($\approx$ 0.30480061 m), retained specifically for geodetic surveying and the State Plane Coordinate System. The two differ by exactly 2 parts per million — immaterial at the scale of an individual lot, but capable of accumulating into a measurable positional discrepancy over the distances typical of state-plane or statewide coordinate work.

Key Result

Acting under National Institute of Standards and Technology (NIST) and NGS authority, the United States deprecated the U.S. survey foot effective December 31, 2022 (Federal Register notice 85 FR 62698), with the international foot becoming, from January 1, 2023 onward, simply "the foot" for NSRS purposes. Legacy SPCS 27 and SPCS 83 coordinates are explicitly not *being recomputed or renamed as a result: NGS will continue to support the U.S. survey foot for those legacy systems, since roughly 40 states officially specify it in their existing SPCS 83 statutes. The deprecation applies going forward, specifically to SPCS2022 and the broader modernized NSRS, for any state that had used the U.S. survey foot in its legacy system.*

This detail interacts directly with the metadata discipline this chapter argues for. A dataset labeled simply "feet," without specifying which of the two definitions applies and relative to which system (legacy SPCS 83 versus SPCS2022), is — after January 1, 2023 — an ambiguous artifact in a way it was not before, precisely because "foot" now has an official, singular meaning that a pre-2023 dataset may silently contradict. Industry guidance converges on a single practical figure for the resulting risk: at the scale of an individual property, the 2 ppm discrepancy is, in the words of one professional trade publication, of the order of one-eighth of an inch per mile — negligible for casual use, but large enough, at the scale of a full state-plane zone (Chapter 19), to matter for anyone chaining long baselines or working near a zone boundary.

Epistemic Notice

This chapter reports the 2 ppm figure and the exact defining ratios (0.3048 m and 1200/3937 m) as established, non-controversial engineering constants confirmed by multiple independent trade sources (*The American Surveyor*, Esri's *ArcNews*, the Wisconsin State Cartographer's Office, and others), not as a figure requiring the same evidentiary caution as the volume's geodetic accuracy claims proper. The qualitative "one-eighth of an inch per mile" comparison is reported as a single trade-press framing device for intuition, not as an independently recomputed value.

29.4 Metadata as the actual load-bearing structure of the transition

A recurring theme across the trade and industry sources consulted for this chapter — distinct in emphasis from, but consonant with, the epoch-and-metadata discipline already argued for on geodetic grounds in Chapter 12 — is that correct metadata, not any particular software feature, is what will actually determine whether an organization's transition goes smoothly. One analysis aimed at asset-management and engineering-owner audiences frames the point in explicitly operational terms: contract language that casually specifies "State Plane" or "NAD 83" will, once NATRF2022 is official, be too vague to be actionable, since frame and epoch will both need to be specified; historical datasets may require dual representation during the overlap period; and procurement specifications and QA/QC procedures alike will need to validate explicit CRS, epoch, geoid-model, and unit metadata rather than assuming a single implicit convention, as was largely possible under the static NAD 83/NAVD 88 regime. A parallel account from the Canadian side of the trilateral coordination effort (Chapter 28) makes the same point from the software-vendor angle: correct metadata is described there as what actually allows a NAD83/NATRF2022 migration to be automated at all, since without it the migration is, in the words of the Canadian Geodetic Survey official quoted, "not really possible."

Key Result

The practical burden of the NATRF2022/NAPGD2022 transition, for the ordinary practitioner, is concentrated less in the geodetic mathematics (handled, largely invisibly, by NCAT and the vendor tools built on it — Chapter 13) and more in three concrete preparatory tasks documented across the sources consulted: (i) verifying, dataset by dataset, current vendor support for the specific software in use; (ii) auditing legacy data for unlabeled or ambiguous foot-definition usage, given the January 2023 deprecation; and (iii) upgrading contract, procurement, and internal metadata standards to require explicit frame, epoch, and geoid-model fields rather than an implicit single-system assumption.

Chapter 30

NCAT and VDatum: The Practitioner's Transformation Toolkit

30.1 From concepts to a button to press

Chapter 13's fourteen-parameter time-dependent Helmert transformation, and Chapter 16's account of the IFVM residual-velocity grid, describe *what* relates NAD83(2011)/NAVD88 coordinates to NATRF2022/NAPGD2022 coordinates. Chapter 29 already surveyed, at the level of practitioner tasks and checklists, what individual firms need to prepare. This chapter fills the remaining gap between the two: the actual software NGS provides so that a working surveyor or GIS analyst never has to implement the transformation mathematics directly.

30.2 Two tools, one codebase

NGS's stated transformation strategy centers on two overlapping web- and desktop-deployable tools: the NGS Coordinate Conversion and Transformation Tool (NCAT), and VDatum, developed jointly by NGS, NOAA's Office of Coast Survey, and the U.S. Army Corps of Engineers. Despite distinct histories and, historically, distinct emphases — NCAT oriented toward geometric (horizontal and ellipsoidal-height) conversions and transformations, VDatum toward vertical and orthometric-height work, including the tidal and hydrographic datums outside this volume's primary scope — NGS states that the two tools share the same underlying codebase, and that results between them should be numerically consistent; NGS's own published FAQ treats any observed discrepancy between NCAT and VDatum output as a reportable bug rather than an expected difference in method.

Key Result

NGS explicitly distinguishes, in its practitioner guidance, between conversion *(a change of coordinate representation within a single reference frame and epoch — geographic to State Plane, for instance) and* transformation *(a change of underlying reference frame, datum, or epoch, potentially combined with a conversion in the same step). NCAT is designed to perform both operations, together, in a single user action: a practitioner can request State Plane NAD83(2011) coordinates transformed directly into SPCS2022 NATRF2022 coordinates without separately invoking the geometric transformation and the projection formulas of Chapter 21 by hand.*

30.3 A worked limitation: WGS84 is not a menu option

One recurring practical friction, documented directly in NGS's own NCAT FAQ, is instructive precisely because it exposes an asymmetry the tool's design otherwise hides. WGS84 — the reference frame nearly all consumer and many professional GNSS receivers report positions in by default — does not appear as a selectable frame within NCAT. NGS's stated workaround is procedurally simple but conceptually notable: the practitioner is instructed to first pass WGS84 coordinates through HTDP (Chapter 16) to obtain NAD83 coordinates, and only then submit the NAD83 result to NCAT for further conversion or transformation. The instruction implicitly reuses HTDP — the very tool Chapter 16 describes NGS as philosophically superseding with the IFVM/IFDM approach for the modernized frames themselves — as a still-necessary front-end utility for a different, adjacent problem: bridging from a global GNSS-broadcast frame family to the NAD83 family, a task the modernized frames' own transformation chain does not yet directly address for the practitioner in a single step.

Epistemic Notice

NGS's FAQ describes this WGS84 gap as provisional ("future versions of NCAT may support WGS84"), not as a permanent design decision; no publication date for such a future version was located among the sources consulted for this volume, and this chapter reports the HTDP-first workaround as NGS's current stated guidance rather than as a stable long-term feature of the toolkit.

30.4 What the tools will and will not do at scale

A second documented limitation concerns automation. NGS's FAQ states plainly that the NCAT web service offers no batch-processing mode: each transformation request is a single coordinate, submitted individually, whether through the web interface or its associated web-service API. For an individual survey point or a handful of control marks this is immaterial; for a GIS department needing to transform an entire parcel layer, a statewide infrastructure database, or a legacy engineering drawing archive, it is a substantive constraint, and NGS's own guidance for such users — reported already in Chapter 29 in the context of firm-level preparation — points toward NCAT and VDatum's downloadable, locally installable versions, or toward direct incorporation of the NGS-provided transformation code into third-party GIS and CAD software, rather than toward the hosted web tool.

Key Result

NGS explicitly frames third-party incorporation, not exclusive reliance on its own web interface, as the intended path for high-volume transformation work: developers are invited to embed the official NCAT/VDatum transformation logic directly into their own software, and NGS states it will maintain published test datasets so that any third-party implementation — an Esri toolbox, a survey-software plugin, a state DOT's internal pipeline — can be checked against the same authoritative reference values NCAT itself uses, rather than against an independently re-derived approximation.

30.5 A staged rollout, not a single release date

Consistent with the beta/alpha product architecture already described in Chapter 24, NCAT and VDatum's modernized-frame capability has itself been released incrementally rather than as a single cutover: an early alpha-site version supporting SPCS2022 conversions preceded full NATRF2022/NAPGD2022 transformation support on the public-facing beta and,

subsequently, production tools, mirroring the staged component-by-component testing period (2024–2026) already documented for the modernization's geodetic products themselves. A practitioner consulting NCAT during this window should therefore expect the tool's supported frame list to have grown over the testing period, rather than assume that an absence of a given modernized product at one point in time reflects a permanent limitation.

Epistemic Notice

This chapter's account of NCAT and VDatum is drawn from NGS's own tool documentation, FAQ pages, and a state geodetic-authority training summary (Wisconsin State Cartographer's Office) rather than from direct hands-on testing of the software by this volume's author; no independent verification of transformation output accuracy was attempted, consistent with this volume's general practice of reporting NGS's stated tool behavior rather than re-deriving it.

Chapter 31

A Global Precedent: GDA2020 and the Logic of Plate-Fixed Datums

31.1 Why look to Australia

Chapter 23 drew a domestic historical comparison, against the 1986 NAD 27→NAD 83 transition, to isolate what genuinely repeats across US datum modernizations and what is new this time. A comparably instructive comparison, this time international and contemporary rather than domestic and historical, is available in Australia's Geocentric Datum of Australia 2020 (GDA2020), officially adopted in 2020 and still in active rollout across Australian jurisdictions as this volume goes to press. The comparison is unusually apt for a structural reason: Australia sits on the fastest-moving major continental plate on Earth, and its geodetic community faced, roughly a decade ahead of NGS, the identical underlying problem this volume's opening chapter poses (Chapter 1) — a static, plate-fixed national datum drifting steadily out of alignment with the geocentric, globally consistent frames that GNSS receivers actually operate in.

31.2 The shared diagnosis: a plate that will not hold still

Geoscience Australia gives the Australian plate's motion as approximately 7 cm per year toward the north-northeast, among the fastest of any major tectonic plate. Left uncorrected since the 1994 definition of GDA94, this drift accumulated, by 2020, into a discrepancy Geoscience Australia and the Intergovernmental Committee on Surveying and Mapping (ICSM) describe consistently across their public materials.

Key Result

GDA2020 shifted Australian national coordinates by approximately 1.8 m to the northeast relative to GDA94, with regional variation — the New South Wales state mapping agency gives a smaller, state-specific figure of approximately 1.5 m for that jurisdiction, while other technical accounts of the transition report a range of roughly 1.5 m in the south-east to 1.8 m in Western Australia. A peer-reviewed account of GDA2020's production (Journal of Spatial Science, 2023) confirms the shift is attributable almost entirely to the accumulated tectonic rotation of the Australian plate over the 1994–2020 interval, plus a small (6–11 cm) step in ellipsoidal heights arising from the adjustment methodology itself.

The parallel to the NAD 83→NATRF2022 case (Chapter 23) is immediate: both transitions report a horizontal shift of the same order of magnitude (Australia's ∼1.5–1.8 m against the US's NGS-stated ∼1–2 m, up to ∼4 m in places), both attribute that shift over-

whelmingly to accumulated tectonic motion rather than to any change in survey technique, and both pair the coordinate shift with a smaller, secondary vertical-datum adjustment.

31.3 The structural parallel: a two-stage design, not a single jump

The most striking parallel, however, is architectural rather than numerical. The Australian modernization was explicitly planned as a two-stage project. Stage 1 delivered GDA2020 itself: a new, but still static, plate-fixed datum that simply re-anchored Australian coordinates to their 2020 position, exactly as NATRF2022 re-anchors North American coordinates to ITRF2020 at epoch 2020.00 (Chapter 2). Stage 2, following in short order, introduced the Australian Terrestrial Reference Frame (ATRF2014), a genuinely time-dependent, GNSS-native frame in which every coordinate carries an explicit epoch and continuous plate motion is modeled directly, rather than corrected for only at the next multi-decade datum revision.

Epistemic Notice

This volume's four-frame architecture for the modernized NSRS (NATRF2022, PATRF2022, CATRF2022, MATRF2022, each plate-fixed and paired with a continuous intra-frame deformation model, IFDM2022 — Chapter 2) is not a copy of the Australian ATRF design, and no source consulted claims direct institutional borrowing in either direction. The two systems were developed independently, by different national geodetic agencies, on different schedules. What this chapter reports is a structural convergence — both national systems, faced with the same underlying problem of tectonic drift against a geocentric global frame, arrived independently at a broadly similar solution: a static, re-anchored datum for ordinary use, coupled with an explicitly time-dependent frame in which epoch is a first-class citizen of every coordinate.

31.4 A difference of degree: single plate versus four

One structural difference is worth making explicit, since it clarifies rather than undermines the parallel. Australia's entire land territory sits, to a first approximation, on a single tectonic plate, so a single Euler-pole rotation (Chapter 3) suffices to describe the plate's motion relative to ITRF. The jurisdiction covered by the modernized NSRS, by contrast, spans four distinct plates — North American, Pacific, Mariana, and Caribbean — which is precisely why NATRF2022 is one of four parallel frames rather than a single national frame as in the Australian case (Chapter 4 details the specific territorial assignments). The Australian case is, in this sense, the structurally simpler limiting case of the same general architecture: one plate, one frame, one Euler pole, where the US case requires four of each.

31.5 Institutional coordination: ICSM and the FGCS compared

A further parallel worth recording concerns the institutional machinery behind each transition. GDA2020 was produced through the ICSM Geodesy Working Group and its Adjustment Working Group, coordinating Geoscience Australia with every state and territory jurisdiction, in a structure functionally analogous to the Federal Geodetic Control Subcommittee (FGCS) coordination described for the US case in Chapters 24 and 27. Both cases, moreover, produced multiple transformation products of differing rigor for different user needs: ICSM offers a 7-parameter similarity transformation (recommended specifically for GNSS data, and directly analogous to the 14-parameter Helmert transformation discussed

in Chapter 13) alongside two-dimensional conformal grids for planar GIS use — the same multi-tool logic underlying NGS's own NADCON/VERTCON/NCAT toolkit.

Epistemic Notice

The sources consulted for this chapter are geospatial trade press, Geoscience Australia and state-government public information sheets, and one peer-reviewed journal article; none constitutes an NGS or ICSM primary source directly comparing the two systems. The comparison offered here is this volume's own construction, drawn from independently sourced facts about each system, not a comparison already published and merely reported. Readers wishing to pursue quantitative aspects of GDA2020 not covered here — for instance, ATRF2014's own stated positional accuracy specification, comparable to the GEOID2022/NAPGD2022 accuracy figures discussed elsewhere in this volume (Chapter 10) — should consult the ICSM technical manual directly, which was not among the documents fetched in full for this volume.

Chapter 32

Bottom-Up Modernization: The Nebraska Case

32.1 Two ways to build a state-level system

Chapter 20 already contrasted two state-level design philosophies for SPCS2022 itself: North Carolina's choice to retain a single statewide zone, against Ohio's dense layer of 89 low-distortion projection zones. This chapter examines a related but distinct question, concerning not zone design but implementation sequencing: in what order does a state actually build up its portion of the modernized reference system, from individual control marks to a fully usable statewide coordinate infrastructure? Nebraska offers a well-documented, explicitly bottom-up answer to that question.

32.2 County, then region, then state

In an extended conversation with Nebraska State Surveyor Casey C. Sherlock, reported by a GIS industry blog specializing in the transition, Sherlock describes Nebraska's approach as proceeding deliberately from the local to the general: new specifications are established first at the county level, then progressively extended upward to regional and finally statewide scope.

Key Result

Nebraska's stated implementation sequence — county-level specification first, then regional aggregation, then a new statewide datum realization — inverts the top-down sequencing implicit in a purely national rollout (NGS core network densification, followed by state adoption). The state's own local control infrastructure is treated as the foundation the statewide system is built up from, rather than as a downstream consumer of a nationally imposed layer.

This sequencing has a concrete operational counterpart: continuous submission of Online Positioning User Service (OPUS) Share observations against both existing and newly established passive geodetic marks, allowing Nebraska's own control network to accumulate the observational history NGS needs to compute reliable reference-epoch coordinates (Chapter 12) for those marks well before the modernized frames become official.

32.3 What this adds to the volume's practitioner-preparation material

Chapter 29 already surveyed the software- and metadata-level preparation tasks facing individual practitioners. The Nebraska case adds the missing institutional layer: a state geodetic authority's own preparation program, distinct from and prior to any individual firm's software readiness checklist. Two elements of Sherlock's account are worth recording as concrete, state-level preparatory tasks, alongside the individual-practitioner tasks already catalogued in Chapter 29:

- **Dataset baseline alignment**: Sherlock's guidance to Nebraska GIS practitioners is to bring all datasets to NAD83(2011) now, as a deliberate intermediate step, specifically to simplify the later reprojection to NATRF2022 — rather than waiting and attempting a single direct jump from whatever legacy realization a given dataset happens to be in.
- **The international-foot transition at the field-collection level**: consistent with Chapter 29's discussion of the U.S. survey foot's deprecation, Sherlock flags field-collection device configuration specifically, since such devices may default to the now-deprecated U.S. survey foot rather than the international foot, and the resulting error — while numerically small per measurement — compounds over the large coordinate values typical of statewide northing/easting work.

Epistemic Notice

This chapter's account of Nebraska's program rests on a single source: an interview-format blog post by a GIS industry commentator, originally published in April 2024 and subsequently updated with an editorial note reflecting the NGS timeline slippage to late 2026 (Chapter 13). It is not an NGS or Nebraska state-government primary source, and no independent verification of the county-then-region-then-state sequencing claim was located among the other sources consulted for this volume. It is reported here, consistent with this volume's sourcing standard for industry and trade material, as a single well-documented practitioner account rather than as an NGS-confirmed statement of Nebraska's official implementation policy.

32.4 A cautionary generalization

It would be a mistake to read Nebraska's sequencing as evidence of a uniform state-level playbook. The sources consulted for this volume document at least three qualitatively different state-level postures toward the same modernization: Ohio's dense, locally-optimized LDP layer and North Carolina's single-zone retention (both design-stage decisions, Chapter 20); and Nebraska's county-up implementation sequencing (an operational, not a design, decision, and orthogonal to the single-zone-versus-many-zones question). Nothing in the sources consulted indicates whether Nebraska's own SPCS2022 zone design follows the North Carolina or the Ohio pattern, and this volume does not speculate on that point in the absence of a source. The three cases are best read as illustrating the range of state-level latitude the modernization's participatory design permits, not as convergent evidence for a single recommended state strategy.

Chapter 33

Uncertainty and Error Propagation in the Modernized NSRS

33.1 Why an accuracy figure is never a single number

Chapter 10 reported NGS's design goal for GEOID2022 in a single figure; this chapter examines what stands behind such figures, and how uncertainty in the modernized NSRS's several component models propagates, compounds, or in some cases partially cancels when a practitioner combines them to compute a real-world position. The distinction that structures this chapter — already implicit but not made explicit elsewhere in this volume — is between *external accuracy*, an empirical figure obtained by comparing model predictions against independent, higher-accuracy check points (typically GNSS-on-benchmark observations), and *internal error*, a formal propagation of the uncertainty already present in the model's own input data and mathematical assumptions. The geodetic literature is explicit that the two need not agree, and that an external-accuracy figure can be misleading on its own if systematic errors are present in the independent check data used to compute it.

33.2 The geoid: a published, tiered accuracy figure

Key Result

NGS reports GEOID2022's estimated accuracy as 1–2 cm in flat terrain and 2–3 cm in mountainous terrain, presented in the NGS Webinar Series progress report on the model. This is consistent with, and appears to operationalize, the more general goal stated in the NOS NGS 64 Blueprint report of maintaining geoid accuracy at 1 cm (one standard deviation) in both absolute and differential geoid undulations, and with the stated ambition of the GRAV-D airborne gravity program specifically, whose goal is a gravimetric geoid accurate to 1 cm where airborne coverage permits.

The terrain dependence itself is worth pausing on, since it is not a detail specific to GEOID2022: it is a structural feature of gravimetric geoid modeling in general, reported consistently in the peer-reviewed literature on the subject. Steep or complex topography requires denser, more accurate input gravity data to reach a given target geoid accuracy than flat terrain does, because the residual terrain correction itself carries larger uncertainty where the topographic mass distribution is less well known; this is the same reason NGS's own accuracy figure degrades by roughly a factor of two in mountainous regions relative to flat ones.

Epistemic Notice

The geoid is not static even at fixed accuracy: Chapter 11's discussion of the geoid's own secular change is directly relevant here, since a geoid accuracy figure quoted for one epoch does not automatically apply, unchanged, at a later epoch without accounting for that drift. NGS's own reported secular geoid-rate range (roughly −1.25 to +1.5 mm/year, per the NOS NGS 69 report cited in Chapter 11) is small relative to the 1–3 cm static accuracy figures reported here, but is not negligible for users who require the two figures to remain jointly valid over a period of a decade or more.

33.3 The deformation model: a genuinely open uncertainty budget

The geometric side of the modernization presents a less settled picture. IFDM2022, the three-dimensional model capturing residual intra-plate deformation not accounted for by each plate's overall Euler-pole rotation (Chapters 2 and 3), was, as of the sources consulted, still under active development through externally funded research grants rather than fully specified as a finished NGS product with a single, published accuracy figure.

Key Result

An NGS-affiliated researcher (identified in the source only by first name, Demián, in the context of an Ohio State University-led modeling effort) is quoted characterizing the expected uncertainty of these time-dependent deformation models as variable and strongly dependent on input-data density, with a target in the centimeter range overall; a comparable, already-operational system in Argentina is cited as empirical precedent, achieving approximately 5 mm uncertainty in tectonically stable regions against roughly 2–3 cm in regions of high deformation.

A concrete illustration of what "high deformation" can mean domestically, cited independently in the same reporting, is the Houston-Galveston region of Texas, an area of substantial land subsidence (driven by groundwater and hydrocarbon extraction rather than by plate tectonics as such) served by its own dense local network of GNSS continuously operating reference stations (the Harris-Galveston Subsidence District's CORS and PAMS stations) precisely because the region's deformation is too localized and too rapid for the continental-scale IFDM2022 model, on its own, to be expected to capture at the same accuracy achieved elsewhere.

Epistemic Notice

No source consulted for this volume provides a single, finalized, nationwide IFDM2022 accuracy specification comparable in authority to the GEOID2022 figures reported above. The centimeter-level target and the Argentine precedent figures are reported here as the best available characterization of the model's *expected* performance, sourced from a named NGS-affiliated researcher speaking informally in an industry newsletter, not from a published NGS technical report with a formal uncertainty budget. This is consistent with this volume's general finding (Chapter 13) that the deformation-model component of the modernization remains, as of mid-2026, comparatively less mature than the geopotential (geoid) component.

33.4 A worked illustration of tectonic-motion propagation

To make the abstract point concrete, consider the published case of NOAA CORS Network station COLA, in Columbia, South Carolina, sitting on stable North American Plate territory rather than in any zone of anomalous local deformation.

Key Result

COLA's published ITRF2020 velocity is approximately 0.05 feet (14 mm) per year. A surveyor observing at COLA in June 2026 would, on this figure alone, expect to see a horizontal shift of roughly 0.3 feet relative to the station's ITRF2020 position at the 2020.00 reference epoch — attributable entirely to ordinary tectonic plate motion accumulated over roughly six years, with no anomaly, subsidence, or measurement error involved. This is precisely the correction the EPP2022/IFDM2022 pairing is designed to apply automatically (Chapter 3): EPP2022 changes the reference frame without changing the epoch, while IFDM2022 changes the epoch without changing the frame, together allowing a raw ITRF2020 observation at any epoch to be converted into a NATRF2022 reference-epoch coordinate consistent with all others.

33.5 The compounding, and partial cancellation, of uncertainty sources

Drawing the geometric and geopotential threads of this chapter together: a full orthometric-height determination under NAPGD2022 combines at least three distinct uncertainty sources examined in this volume — the GNSS-derived ellipsoidal height itself (subject to ordinary GNSS positioning error, not treated in this chapter), the geoid undulation from GEOID2022 (1–2/2–3 cm, terrain-dependent, as above), and, where the observation and the reference epoch differ, the IFDM2022/EPP2022 epoch-propagation correction (centimeter-level in stable regions per the Argentine precedent, larger in known high-deformation zones such as Houston-Galveston). These sources are not generally correlated with one another — a GNSS receiver's instantaneous positioning error has no structural relationship to a region's long-term tectonic deformation rate — and so combine, to first order, in quadrature rather than by simple addition; but the practical implication for a working surveyor is simpler than the formal error-propagation rule: the geoid-model term and the deformation-model term are each independently capable of contributing a comparable few-centimeter share of the total budget, and a practitioner working in a region of anomalous deformation (Houston-Galveston being the clearest domestic example documented) should expect the deformation term, not the geoid term, to dominate the final uncertainty.

Epistemic Notice

This closing synthesis is this volume's own construction, combining figures independently reported for GEOID2022 and for IFDM2022/EPP2022 in the sources cited throughout this chapter; no single source consulted presents a combined, end-to-end uncertainty budget for a NAPGD2022 orthometric height computed via GNSS. The quadrature-combination framing follows standard error-propagation practice for independent error sources, not a NGS-published combination formula specific to NAPGD2022.

Chapter 34

Sinking Faster Than the Datum: Louisiana and the Chesapeake

34.1 Why a static vertical datum fails fastest at the coast

Chapter 32 examined implementation sequencing in a state where the modernization's central challenge is organizational; Chapter 18 examined a state where a single Euler pole cannot capture the underlying crustal kinematics. This chapter turns to a different kind of stress test, one that concerns not the horizontal frame but the vertical datum of Chapters 6–11: two U.S. coastal regions, the Louisiana Gulf Coast and the southern Chesapeake Bay, where land subsidence proceeds fast enough, and unevenly enough, that a static orthometric-height reference — NAVD 88's own original design — becomes practically unusable within a working lifetime, for reasons that have nothing to do with the geoid model's own accuracy and everything to do with the ground moving out from under the benchmark.

34.2 Louisiana: the fastest-sinking large coastal region in the country

The scale of the Louisiana problem was first established at the pace required to matter operationally by Roy K. Dokka's re-analysis of historical leveling data, published as NOAA Technical Report NOS NGS 50. Dokka's central finding, cross-checked against independent tide-gauge records and a handful of early Continuously Operating Reference Station (CORS) time series, was that subsidence rates in the lower Mississippi Valley and northern Gulf Coast were substantially higher than earlier leveling- or geology-based estimates had suggested, exceeding 25 mm/yr in the Mississippi River delta and the chenier plain of southwest Louisiana.

Key Result

NOAA Technical Report NOS NGS 50 (Shinkle and Dokka, 2004) reports leveling-derived subsidence rates agreeing with independent tide-gauge rates to within about 1.5 mm/yr, and with CORS-derived rates at three stations to within about 2 mm/yr, over the highest-subsidence portion of coastal Louisiana — three independent geodetic techniques converging on the same conclusion: land in this region is sinking, relative to the reference frame's fixed plate, faster than any comparably sized coastal region elsewhere in the CONUS domain.

The practical consequence for a static datum is direct. A benchmark whose published NAVD 88 elevation is correct at the moment of its last leveling survey degrades, at 25 mm/yr, by roughly one foot of accumulated error every decade — an error an order of magnitude

larger than the few-centimeter accuracy NGS targets for GEOID2022 itself (Chapter 11), and one that a geoid model, however accurate, cannot correct, because the discrepancy is a change in the physical elevation of the mark, not an error in the equipotential surface it is referenced to.

Epistemic Notice

Subsidence-rate figures for coastal Louisiana vary substantially by source, method, and subregion, and the literature itself is not fully reconciled: a 2021 Louisiana Coastal Protection and Restoration Authority technical report gives a range of roughly 4–18 mm/yr across the coast depending on location (highest in the Mississippi Bird's-Foot Delta, lowest in the western Chenier Plain and around Lake Pontchartrain's north shore), while shorter GPS time-series studies (2016–2020 GNSS data) report rates as low as roughly 2–8 mm/yr at specific stations once seasonal hydrologic loading is removed. This chapter reports the range as documented rather than resolving it to a single number, consistent with this volume's practice of flagging unreconciled figures rather than averaging them into a spurious precision.

34.3 From a research network to a state standard: GULFNet and the LSRC

Louisiana's institutional response predates, and directly anticipates, the CORS-centric access paradigm this volume describes as central to the modernized NSRS (Chapter 15). Recognizing that traditional passive benchmarks were themselves subsiding and therefore unreliable as fixed vertical control, Dokka — then at Louisiana State University — built a network of continuously operating GPS reference stations, GULFNet, using antennas mounted on geologically stable structures rather than ground-set monuments. In 2002 this effort was formalized as a partnership between LSU's Center for GeoInformatics (C4G) and NGS, creating the Louisiana Spatial Reference Center (LSRC) and, subsequently, state legislation making the CORS network itself the vertical control standard for Louisiana — a state-level anticipation, roughly two decades early, of the access-through-CORS-rather-than-through-passive-marks paradigm this volume documents as one of the modernization's defining features nationally.

Key Result

Louisiana adopted a continuously operating GNSS network as its legal *vertical control standard specifically because differential leveling to passive benchmarks could not keep pace with documented subsidence rates of 25 mm/yr or more — the same underlying problem the modernized NSRS's time-dependent, epoch-tagged coordinates (Chapter 12) are designed to solve nationally, worked out as a practical state-level necessity roughly twenty years before NAPGD2022's national rollout.*

34.4 Chesapeake Bay: a slower, doubly-caused sinking

The southern Chesapeake Bay region illustrates a related but mechanistically distinct problem: subsidence here proceeds an order of magnitude more slowly than in Louisiana, but from two superimposed, well-separated causes rather than one. The first is glacial isostatic adjustment (GIA): the region sits within the collapsing forebulge of the former Laurentide ice sheet, a slow-motion process NGS's own public-education materials estimate will sink land around the Bay by as much as half a foot over the next century from GIA alone. The second, and larger, contributor is anthropogenic aquifer compaction: a 2013 USGS study (Eggleston and Pope, Circular 1392) attributes more than half of observed land subsidence in the southern Chesapeake Bay region to compaction of the Potomac aquifer system from groundwater withdrawal, at rates of roughly 1.5–3.7 mm/yr, superimposed on the GIA signal.

Key Result

A 2025 GNSS-based vertical land motion study of the Chesapeake Bay region (combining five years of campaign GPS at over 60 sites with continuous data from 120 CORS-type stations) reports subsidence rates of −2.97 to −0.40 mm/yr across the region — confirming that GIA and aquifer compaction are both active, spatially variable, and, unlike Louisiana's storm- and sediment-compaction-driven subsidence, largely independent of any single dominant local process, which is precisely why the two causes must be geodetically separated rather than reported as a single regional average.

Epistemic Notice

The relative contribution of GIA versus aquifer compaction to Chesapeake Bay subsidence is itself a point of active scientific and public discussion rather than a fully settled figure; the USGS Circular 1392 estimate (aquifer compaction as the majority contributor) and the NGS forebulge-collapse public estimate (GIA alone accounting for roughly half a foot over a century) are drawn from different studies with different scopes, and this volume reports both without adjudicating a single combined attribution, consistent with its no-invented-data standard.

34.5 What the two cases add, together, to the volume's argument

Louisiana and the Chesapeake sit at opposite ends of a single spectrum the modernized vertical datum is built to span: from a fast, spatially concentrated, largely sediment-and-fluid-driven subsidence in the Mississippi Delta, to a slow, spatially diffuse, dual-caused (natural and anthropogenic) subsidence in the mid-Atlantic. NAPGD2022's architecture — a static geoid component (SGEOID2022) combined with a separately maintained, updatable crustal-velocity layer (Chapter 16's IFVM/IFDM machinery) rather than a single fixed height network — is designed precisely to accommodate both extremes within one national framework, without requiring, as NAVD 88 effectively did in practice, a state-by-state ad hoc workaround of the kind Louisiana had already been forced to invent two decades before the national modernization reached it.

Epistemic Notice

This chapter's Louisiana subsidence figures are drawn from NOAA Technical Report NOS NGS 50, a 2021 Louisiana CPRA technical report, and a peer-reviewed GNSS hydrologic-loading study; its Chesapeake figures are drawn from a USGS circular, NGS public-education material, and a 2025 peer-reviewed GNSS vertical-land-motion study. None of these sources are NGS's own NAPGD2022 product documentation, and none report a direct, quantified assessment of how well GEOID2022 or the IFVM crustal-velocity layer specifically resolves either region's subsidence at the accuracy NGS targets elsewhere in this volume; that specific validation, if and when NGS publishes it, lies outside the evidentiary record available for this volume as of July 2026.

Chapter 35

The Combined Height Budget, Formalized: Variance Decomposition and Its Independence Assumptions

35.1 What remained informal in the closing synthesis

Chapter 33 closed by combining the geoid's accuracy figure and the deformation model's accuracy figure "in quadrature," explicitly flagging this synthesis as the volume's own construction rather than a published NGS formula. Chapter 14 then formalized a structurally related combination — the propagation of coordinate covariance through the fourteen-parameter Helmert transformation — but did not return to the scalar height case that motivated the quadrature language in the first place. This chapter closes that gap: it writes the orthometric-height computation as an explicit functional model, derives the variance of the result from the general propagation law already stated in Chapter 14, and states, as declared hypotheses rather than as facts drawn from any source, the independence assumptions the quadrature combination requires.

35.2 The functional model

A practitioner computing a NAPGD2022 orthometric height H from a GNSS observation combines three quantities discussed separately in this volume:

$$H = h - N(\varphi, \lambda) + \delta(t, t_0),$$

where h is the GNSS-derived ellipsoidal height at the observation epoch t, $N(\varphi, \lambda)$ is the GEOID2022 undulation at the observation point (Chapters 10 and 11), and $\delta(t, t_0)$ is the epoch-propagation correction supplied by IFDM2022/EPP2022 when the observation epoch t differs from the reference epoch $t_0 = 2020.00$ (Chapters 16 and 3). This is the same three-term decomposition Chapter 33 discussed in prose; writing it as a single equation is what allows the propagation law to be applied to it directly.

35.3 Applying the general propagation law

Treating h, N, and δ as the three input quantities $\mathbf{x} = (h, N, \delta)$ and $H = f(\mathbf{x})$ as a scalar output, the general law already stated in Chapter 14 reduces, for a scalar function of three

inputs with covariance matrix Σ_x, to

$$\sigma_H^2 = \mathbf{J}\,\Sigma_x\,\mathbf{J}^T, \qquad \mathbf{J} = \left(\frac{\partial H}{\partial h}, \frac{\partial H}{\partial N}, \frac{\partial H}{\partial \delta}\right) = (1,\, -1,\, 1),$$

which, written out in full with the three pairwise covariance (correlation) terms explicit, is

$$\sigma_H^2 = \sigma_h^2 + \sigma_N^2 + \sigma_\delta^2 \;-\; 2\,\mathrm{Cov}(h, N) \;+\; 2\,\mathrm{Cov}(h, \delta) \;-\; 2\,\mathrm{Cov}(N, \delta).$$

Key Result

Quadrature combination — $\sigma_H^2 = \sigma_h^2 + \sigma_N^2 + \sigma_\delta^2$, the form used informally in Chapter 33 — is not a separate approximation to this expression; it is this same exact expression under the specific condition that all three covariance terms vanish. The propagation law derived here does not itself establish that condition: it only shows precisely what must be true of h, N, and δ for the informal quadrature step to be exact rather than merely a plausible simplification.

35.4 The independence hypotheses, stated explicitly

Three pairwise-independence hypotheses are needed for the cross-covariance terms above to vanish. None of them is established, in this volume or in any source it consulted, by a published joint calibration study; each is stated here as an explicit working hypothesis, together with the physical reasoning offered in its support.

- **H1, $\mathrm{Cov}(h, N) = 0$.** The GNSS ellipsoidal-height error h is dominated by satellite-orbit error, tropospheric delay, multipath, and receiver-antenna effects at the observation site; the GEOID2022 undulation error N is dominated by gravity-data density and the residual terrain correction (Chapter 33). The two error budgets are built from disjoint physical processes and disjoint input datasets (GNSS tracking data versus airborne and terrestrial gravity data), which is the substantive content of H1: it is a claim about the physical independence of two measurement chains, not a mathematical derivation.
- **H2, $\mathrm{Cov}(h, \delta) = 0$.** The epoch-propagation correction δ is derived from the CORS velocity network underlying IFDM2022 (Chapter 16), a dataset accumulated over years of continuous tracking and materially decorrelated, session to session, from any single observation's instantaneous GNSS error. H2 asserts that a single, present-epoch positioning error carries no structural relationship to a long-term, network-averaged velocity-field estimate.
- **H3, $\mathrm{Cov}(N, \delta) = 0$.** This is the least secure of the three. GEOID2022 and IFDM2022 are estimated from distinct primary datasets (gravity observations versus GNSS velocity observations) and are not, as far as this volume's sources indicate, jointly adjusted or cross-calibrated against one another. H3 is offered as the default assumption in the absence of any documented joint-estimation procedure, not as a claim that no physical mechanism could correlate the two.

Epistemic Notice

H1–H3 are this volume's own explicit hypotheses, introduced to make precise the condition under which Chapter 33's informal quadrature combination is exact. No source consulted for this monograph reports a measured correlation coefficient, positive or negative, between any pair of (h, N, δ); the physical reasoning offered for each hypothesis is the author's own argument from the disjointness of the underlying measurement processes, not a finding attributed to NGS or to the geodetic literature cited elsewhere in this volume.

35.5 A documented case where H3 is known to fail: glacial isostatic adjustment

The one mechanism identified in this volume's own sources with the structural capacity to violate H3 specifically is glacial isostatic adjustment (GIA): the slow post-glacial rebound process that Chapter 11 already identified as one contributor to the geoid's secular rate of change, and that is simultaneously a documented contributor to vertical land motion in the same formerly glaciated regions IFDM2022 is designed to capture. A region undergoing active GIA therefore has, in the same location, a non-zero geoid secular rate *and* a non-zero deformation-model correction driven, at least in part, by the same underlying geophysical process — precisely the shared-mechanism scenario H3 is stated to exclude by assumption elsewhere.

Epistemic Notice

This section identifies GIA as the one physically named mechanism, among this volume's own sources, capable of correlating N and δ in specific regions; it does not attempt to quantify that correlation, since no source consulted publishes a joint GIA-attributable covariance figure for GEOID2022 and IFDM2022. The practical implication — that H3 should be treated as a default rather than a universal fact, and relaxed first in known formerly-glaciated regions if a practitioner requires a rigorous rather than approximate combined budget there — is this volume's own inference from the disjunction it has documented, not a warning issued by NGS.

35.6 A numeric range under H1–H3, using figures already reported in this volume

Taking H1–H3 as given, and using only the accuracy figures already reported in Chapter 33 — GEOID2022 at 1–2 cm (flat terrain) or 2–3 cm (mountainous terrain), and the Argentine-precedent characterization of IFDM2022 at roughly 5 mm in tectonically stable regions against 2–3 cm in regions of high deformation such as Houston-Galveston — the propagation law above gives, purely as an application of the arithmetic already licensed by the hypotheses stated:

$$\sigma_H \approx \sqrt{(1\text{–}2)^2 + (0.5)^2}\ \text{cm} \approx 1.1\text{–}2.1\ \text{cm} \quad \text{(flat terrain, tectonically stable)},$$

$$\sigma_H \approx \sqrt{(2\text{–}3)^2 + (2\text{–}3)^2}\ \text{cm} \approx 2.8\text{–}4.2\,\text{cm} \quad \text{(mountainous terrain, or a high-deformation zone)}.$$

Epistemic Notice

These two numeric ranges are arithmetic consequences of figures already reported and sourced in Chapter 33, combined here under the explicit hypotheses H1–H3 stated above; they are not an additional published NGS or CGS figure, and they inherit every caveat already attached to the underlying numbers there — in particular, the fact that no single, finalized, nationwide IFDM2022 accuracy specification exists, so the 5 mm/2–3 cm figures entering the second term remain a researcher's informal characterization rather than a formal product specification.

35.7 What this chapter adds, and what it does not

This chapter's contribution is the explicit functional model $H = h - N + \delta$, the resulting exact variance decomposition with its three cross-covariance terms, and the isolation of H1–H3 as the specific, named hypotheses under which that decomposition collapses to the quadrature form used informally in Chapter 33. It is, in this respect, the scalar-height counterpart of the coordinate-covariance formalization Chapter 14 carried out for the Helmert transformation:

both chapters take a quadrature step stated informally elsewhere in this volume and derive the exact condition, from the standard geodetic propagation-of-errors law, under which that step is not merely a reasonable simplification but an equality. Neither chapter, and no other chapter of this volume, supplies the one thing that would let a practitioner move from hypothesis to measured fact: a published, joint covariance estimate between GEOID2022 and IFDM2022 errors. In its absence, H1–H3 remain this volume's own explicit, physically motivated working assumptions.

Appendix A

Elements of Geopotential Field Theory

This appendix collects, in synthetic form and derived from NGS Blueprint Part 2 (Appendix B), the minimal elements of geopotential field theory needed to fully understand the equations discussed in Chapters 7 and 10. It does not claim to be exhaustive: for a complete treatment, the Blueprint itself refers to the classic textbooks of physical geodesy (Heiskanen and Moritz, 1967; Hofmann-Wellenhof and Moritz, 2006).

Gravitation, centrifugal force, gravity

Geodesists carefully distinguish three notions often conflated in everyday language:

- **Gravitation** — the attractive force between two masses, according to Newton's universal law of gravitation;
- **Centrifugal force** — a fictitious force, due to the uniform circular motion of a body co-rotating with the Earth;
- **Gravity** — the force acting on a body on or near the Earth's surface, a combination of the two preceding forces.

The gravitational potential generated by a point mass is given by $V = Gm/s$, where G is the universal gravitational constant, m the mass, and s the distance. Summing the contribution of all the masses that make up the Earth yields the Earth's gravitational potential field. The centrifugal potential is $\Phi = \frac{1}{2}\omega^2 p^2$, where ω is the Earth's angular rotation velocity and p the distance from the point to the rotation axis. The total gravity potential is the sum:

$$W = V^{(1)} + \Phi,$$

where $V^{(1)}$ denotes the "true" gravitational potential, to distinguish it from the simpler "normal" potential $V^{(2)}$ used in some simplified formulations.

Spherical Harmonic Models (SHM)

Spherical Harmonic Models (SHM), such as EGM96, EGM2008, and EGM2020, represent the Earth's external gravitational potential as a series of spherical harmonics up to a maximum degree N chosen by the modeler (for GM2022, $N = 2190$, see Chapter 7). An SHM is valid only in "harmonic" space, i.e. outside the Earth's solid masses; for this reason an SHM alone,

however high its degree N, can never provide a model of the geoid, which by definition lies inside the continental masses (where the field is not harmonic). This limitation — known as the first of an SHM's three structural limits, together with *omission error* (loss of spectral detail beyond the maximum degree N) and *commission error* (imperfect determination of the coefficients themselves) — is why NGS builds GEOID2022 as a derived gridded product, not as a direct evaluation of GM2022.

The spherical harmonic expansion, explicitly

In geocentric spherical coordinates (r, θ, λ) (radius, co-latitude, longitude), the gravitational potential $V^{(1)}$ outside all of the Earth's masses is written, in the form actually used to build models such as GM2022, as

$$V^{(1)}(r,\theta,\lambda) = \frac{GM}{r}\left[1 + \sum_{n=2}^{N}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^n \bar{P}_{nm}(\cos\theta)\Big(\bar{C}_{nm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda\Big)\right],$$

where GM is the geocentric gravitational constant, a a reference radius (close to the Earth's equatorial radius), $\bar{P}_{nm}$ the fully normalized associated Legendre functions, and $\bar{C}_{nm}, \bar{S}_{nm}$ the (fully normalized) spherical harmonic coefficients determined from satellite, terrestrial, and airborne gravimetric data. The pair (n, m) — degree and order — indexes the spatial wavelength of each term: low degree captures the broad, continental-scale shape of the field, while high degree captures short-wavelength, local detail. For GM2022, $N = 2190$ (Chapter 7).

Key Result

The maximum degree N of a spherical harmonic model fixes, by a standard rule of thumb in physical geodesy, the shortest spatial half-wavelength $\lambda_{\min}$ that the model can in principle resolve:

$$\lambda_{\min} \approx \frac{2\pi a}{2N} = \frac{\pi a}{N}.$$

With $a \approx 6378$ km and $N = 2190$, this gives $\lambda_{\min} \approx 9.1$ km — consistent, as an order of magnitude, with the 1-arcminute (roughly 1.8 km at mid-latitudes) grid spacing adopted for the derived SGEOID2022/SDEFLEC2022 products (Chapter 7), which oversample the harmonic model's own resolution limit to avoid introducing additional interpolation error. This is a direct mathematical consequence of the chosen degree N, not an independently measured quantity, and is reported here for that reason as a keyresult rather than a disclaimerbox item.

From potential to geoid undulation: Bruns' formula

The link between the abstract spherical harmonic model above and the geoid undulation grids N actually distributed to users (Chapter 7) passes through the disturbing potential $T = W - U$, the difference between the real potential W and a chosen reference ("normal") potential U generated by an equipotential reference ellipsoid such as GRS 80. Bruns' formula (Bruns, 1878) relates the geoid undulation directly to T:

$$N = \frac{T}{\gamma},$$

where γ is normal gravity on the reference ellipsoid. This is the formula, applied point by point across the modeled domain, that in practice turns a spherical harmonic model (plus terrain and residual gravimetric corrections) into the gridded SGEOID2022 product. It is

also the formula implicitly invoked whenever this volume treats a change in geopotential (ΔW) and a change in height (ΔN) as interchangeable up to a factor of γ — see for instance the threshold calculation in Chapter 9.

Two structural error sources, quantified: Kaula's rule

Appendix A's main text already named *omission error* and *commission error* as the two structural limits of a spherical harmonic model beyond the harmonicity restriction. Both admit a simple, classical quantification. A widely used empirical rule for the expected order of magnitude of the (dimensionless) degree variance of the geopotential coefficients themselves, due to Kaula (1966), is

$$\sigma_n \approx \frac{10^{-5}}{n^2},$$

where $\sigma_n^2 = \sum_{m=0}^{n}(\bar{C}_{nm}^2 + \bar{S}_{nm}^2)$. Two consequences follow directly, both relevant to how GM2022/GEOID2022 are used elsewhere in this volume:

- **Omission error** — the geoid undulation signal left out by truncating the expansion at degree $N = 2190$ is, order of magnitude, $\sum_{n>N} \sigma_n \times$ (scale factor): because σ_n falls off as n^{-2}, the omitted signal is dominated by the lowest omitted degrees just above N, not spread evenly across all higher degrees — which is exactly why the 1-arcminute SGEOID2022 grid (Chapter 7) needs additional local gravimetric and terrain data to reach centimeter accuracy, rather than relying on the harmonic model alone up to arbitrarily fine detail.
- **Commission error** — the uncertainty carried by the estimated coefficients $\bar{C}_{nm}, \bar{S}_{nm}$ themselves, driven by the density and quality of the satellite, terrestrial, and airborne data used to determine them; unlike omission error, it does not follow a universal rule like Kaula's and must be estimated empirically for each model, which is precisely why the GSVS validation campaigns of Chapter 6 were necessary in the first place.

Epistemic Notice

Kaula's rule is a classical, general-purpose empirical regularity in physical geodesy (used, for instance, to regularize the estimation of high-degree coefficients), not a figure specific to GM2022 or to NGS documentation. It is reported here as established textbook background (Kaula, 1966; Heiskanen and Moritz, 1967), consistent with the sources Appendix A already refers to, and not as a claim about GM2022's actual, empirically determined error spectrum, which NGS has not to date published in the sources consulted for this volume.

The deflection of the vertical

Bruns' formula links the disturbing potential T to the geoid undulation N through its *magnitude* at a point; the same disturbing potential also carries directional information, used repeatedly but never made explicit elsewhere in this volume whenever it refers to the "SDEFLEC2022" product alongside SGEOID2022 (Chapter 7). The *deflection of the vertical* is the small angle between the direction of the true plumb line (the local direction of gravity, normal to the geoid) and the direction of the normal to the reference ellipsoid at the same point. It is conventionally resolved into two components, a north-south component ξ and an east-west component η, obtainable to a good approximation from the horizontal gradient of the geoid undulation itself:

$$\xi \approx -\frac{\partial N}{\partial x}, \qquad \eta \approx -\frac{\partial N}{\partial y}\cos^{-1}\varphi,$$

where x, y denote local north and east distances and φ the geodetic latitude — in words, the deflection of the vertical is, to first order, simply the local slope of the geoid relative to the ellipsoid. The historical route to computing ξ, η directly from surface gravity data, without first passing through N, is the Vening Meinesz integral formula (1928), the angular counterpart of Stokes' formula for N itself; both integrals take the same gravity-anomaly data as input and differ only in the kernel function applied.

Epistemic Notice

The deflection of the vertical is not a merely theoretical refinement: any observation taken with an instrument leveled to the local plumb line (classical astronomic observations, and more subtly, terrestrial optical surveying instruments more generally) is oriented relative to gravity, not relative to the ellipsoid normal used in GNSS-based geodesy. SDEFLEC2022, cited alongside SGEOID2022 throughout this volume without further definition until now, is precisely the gridded product that lets a user convert between the two orientations at any point in the modernized NSRS.

Molodensky's alternative: normal heights and the quasigeoid

Everything derived so far in this appendix — Bruns' formula, the deflection of the vertical, and by extension GEOID2022 itself as described in Chapter 7 — belongs to the classical, Stokes-based tradition of geoid determination. That tradition has a structural cost easy to overlook: computing the geoid undulation rigorously from surface gravity data requires, in principle, reducing the observed gravity values down through the rock masses between the Earth's physical surface and the geoid (a Bouguer or isostatic reduction), which in turn requires a hypothesis about the density of those masses — a quantity that is not, in general, actually known.

M. S. Molodensky proposed, beginning in 1945 and fully developed with Eremeev and Yurkina by 1960, a reformulation of the boundary-value problem of physical geodesy that avoids this density hypothesis entirely, by working exclusively with quantities defined on or above the Earth's actual physical surface rather than on the (physically inaccessible, mass-laden) geoid. In Molodensky's theory, the *normal height* H^* of a point — rather than its orthometric height H — is obtained by dividing the same geopotential number $C = W_0 - W(P)$ (Chapter 12) used throughout this volume not by the true mean gravity $\bar{g}$ along the plumb line (which, again, requires a density hypothesis to estimate for a point below the surface), but by the *normal* mean gravity $\bar{\gamma}$ computed analytically along the normal plumb line of the reference ellipsoid, a quantity that requires no assumption about real subsurface density at all:

$$H^* = \frac{C}{\bar{\gamma}}, \qquad \text{as opposed to} \qquad H = \frac{C}{\bar{g}}.$$

Plotting the corresponding *height anomaly* $\zeta = h - H^*$ (with h the ellipsoidal height, exactly as $N = h - H$ for the orthometric case) above the ellipsoid at every point traces out a surface called the *quasigeoid*, distinct in general from the geoid, though the two coincide exactly over the open oceans (where $H = H^* = 0$ by definition) and differ from one another, over land, typically by a few centimeters in lowlands and by decimeters in high mountain terrain, where the density-hypothesis error the quasigeoid was designed to eliminate is largest.

Key Result

The geoid/quasigeoid distinction is not a footnote internal to physical geodesy: it corresponds to a genuine fork in how a national height system can be built. Some national vertical datums (several in continental Europe, following the tradition established by Molodensky's own country) are defined via normal heights and a quasigeoid model; NAVD 88 and, per the sources this volume relies on for Chapter 7, NAPGD2022 as well, are defined via orthometric heights and a geoid model in the classical Stokes tradition. The choice is not merely terminological: it determines whether a national height system's error budget includes an irreducible density-hypothesis term or not.

Epistemic Notice

This comparison is reported here as general, textbook-level context on the two competing theoretical traditions of physical geodesy (Molodensky, Eremeev, and Yurkina, 1960; Hofmann-Wellenhof and Moritz, 2006), not as a claim independently verified against NGS's own technical specification of the density-reduction (or density-hypothesis-avoidance) procedure actually used to construct GEOID2022/SGEOID2022. A reader who needs the precise reduction scheme NGS applied should consult the relevant NGS technical report directly rather than infer it from this appendix's general framing.

Why this matters for a volume on distortion theory

Epistemic Notice

The reader of this volume, more interested in cartographic distortion theory than in physical geodesy in the strict sense, may regard this appendix as the "under the hood" layer that makes possible the geoid undulation grids discussed in the preceding chapters: without a model, however approximate, of the Earth's gravitational potential field, no reference surface against which to measure an orthometric height would exist, and the entire distinction between ellipsoidal height and orthometric height (Chapter 1) would lose its operational meaning.

Appendix B

A Brief History of Geoid Modeling

This appendix summarizes, drawing on Appendix A of NGS Blueprint Part 2, the history of geoid modeling, a topic that directly touches on the author's long-standing interest in the history of the measurement and representation of space.

From the Nile floods to Gauss

Referencing height to the level of a body of water has a history that the Blueprint itself traces back more than 4,000 years: according to the Palermo Stone, the ancient Egyptians regularly recorded the height of the Nile's annual flood, although the exact datum to which those heights were referred remains uncertain. One must wait until the nineteenth century for the notion of mean sea level to receive an explicit mathematical foundation: Carl Friedrich Gauss proposed, in 1828, a "mathematical figure of the Earth," a concept taken up and developed by George Gabriel Stokes in 1849 with the calculation of the "surface of the Earth's original fluidity." Only a few decades later did this mathematical representation of sea level receive the name we still use today: "geoid" (Listing, 1873).

The century of one-meter approximation

For most of the twentieth century, geoid modeling remained an almost purely theoretical enterprise, limited both by available data and by theory itself: as late as 1967, one of the most authoritative treatises on the subject (Heiskanen and Moritz) could state that an error below one meter in geoid undulation was negligible for practical purposes. The following decades saw rapid progress in data collection, computational power, and modeling theory, to the point that today only errors on the order of millimeters to centimeters are considered negligible — three orders of magnitude of improvement in under sixty years.

From purely gravimetric geoids to hybrid geoids

A turning point occurred in the 1990s: the first US-specific models (GEOID90, GEOID93), based on gravimetric data and pure theory, revealed a discrepancy of several meters relative to NAD 83/NAVD 88 data — a discrepancy attributable, as discussed in Chapter 1, to the non-geocentricity of NAD 83 and to regional biases in NAVD 88. NGS's response, starting in 1996, was the creation of "hybrid geoids" (beginning with GEOID96), which start from a pure gravimetric model but are then corrected to fit the GNSS and leveling data of the then-current NAD83/NAVD88 system. This compromise served the US geodetic community well for two decades, but by construction ties the geoid model to the very defects of the system

it is meant to support — the underlying reason, discussed in Chapter 6, why GEOID2022 deliberately breaks this dependency, returning to a purely gravimetric model.

A parallel tradition: Molodensky and the quasigeoid

The narrative so far has followed a single lineage — Gauss, Stokes, Listing, and the successive American gravimetric and hybrid geoids — because it is the lineage that leads directly to GEOID2022. It was not, however, the only twentieth-century response to the practical difficulties of geoid determination. Working independently in the Soviet Union, M. S. Molodensky proposed in 1945, and fully worked out with P. G. Eremeev and M. I. Yurkina by 1960, an alternative formulation of the boundary-value problem of physical geodesy that sidesteps the density-hypothesis difficulty inherent in the Stokes tradition (Appendix A gives the technical detail): rather than reducing gravity observations down through the Earth's topographic masses to an inaccessible geoid, Molodensky's theory works entirely with quantities defined at or above the physical surface itself, yielding not a geoid but a *quasigeoid*, together with normal rather than orthometric heights.

Epistemic Notice

Molodensky's theory did not displace the Stokes/geoid tradition in the United States, where NGS's own successive models — from GEOID90 through GEOID2022 — have remained within the classical geoid framework described earlier in this appendix. It found its principal institutional home instead in parts of continental Europe and in the Soviet geodetic tradition from which it emerged, several of whose successor national surveys retain quasigeoid-based height systems to this day. Its relevance to this volume's own narrative is therefore less a matter of the specific history of NAPGD2022 — which this appendix traces without reference to Molodensky's line of work — and more a reminder that the "purely gravimetric geoid" choice discussed above, presented in the preceding section as a return to first principles after the hybrid-geoid era, was itself only one of two theoretically rigorous ways available, by the mid-twentieth century, to solve the same underlying problem.

Epistemic Notice

This historical appendix does not claim to replace a specialist treatment of the history of physical geodesy, for which the Blueprint itself refers to classic texts (Heiskanen and Moritz, 1967; Hofmann-Wellenhof and Moritz, 2006). Its purpose, within the economy of this volume, is to show that NGS's contemporary choice — abandoning hybridization in favor of a purely gravimetric geoid — is not an isolated technical whim, but the outcome of a historical trajectory spanning nearly two centuries, of which the 2022–2026 modernization constitutes the latest chapter, certainly not the first.

Appendix C

A Brief History of NAD 83's Realizations

This appendix summarizes, drawing on NGS conference presentations, technical circulars, and the official 2011 National Adjustment FAQ, the successive realizations NAD 83 passed through between 1986 and 2011 — a history that gives the modernization described in the body of this volume its immediate technical prehistory, and that this appendix treats symmetrically to Appendix B's history of the geoid.

1986: a modern datum built with pre-modern instruments

The original realization, NAD 83(1986), replaced NAD 27 as the official U.S. horizontal datum, adopting a geocentric ellipsoid (GRS 80) in place of NAD 27's regional, non-geocentric Clarke 1866 ellipsoid. The datum's underlying geometric concept was therefore already modern, but its observational basis, as NGS's own retrospective presentations note plainly, was not: the 1986 adjustment consisted almost entirely of classical, optical (triangulation and trilateration) observations, the same technology that had produced NAD 27 itself, simply readjusted onto the new ellipsoid and origin. GPS observations played essentially no role in the original 1986 network.

HPGN/HARN: a state-by-state GPS upgrade

Through the late 1980s and into the mid-2000s, NGS and the individual states undertook a rolling program of state-by-state GPS resurveys, known first as the High Precision Geodetic Network (HPGN) and, from the early 1990s onward, as the High Accuracy Reference Network (HARN). Observed over roughly 1989–2004 on a state-by-state rather than simultaneous national basis, and typically involving four-hour GPS sessions occupying a sparse network of new or existing control marks, HARN/HPGN adjustments still incorporated the older classical-observation stations rather than replacing them outright, producing a datum realization — informally NAD 83(HARN) or NAD 83(96), by state — accurate to roughly the centimeter level regionally, a substantial improvement over 1986, but one still computed independently, state by state, rather than as a single simultaneous national solution.

Key Result

Because HARN/HPGN realizations were computed independently, essentially state by state, over a roughly fifteen-year observation window, they introduced small but real discontinuities in coordinate values across *state boundaries even for the same nominal datum tag — an artifact of the network's piecemeal construction that the fully simultaneous national adjustments of 2007 and 2011 were explicitly designed to remove.*

2007: the first GPS-only, simultaneous national solution

The next realization, completed in 2007, was the first to be computed as a single simultaneous nationwide GPS-only adjustment rather than a state-by-state patchwork. It was published under two closely related but formally distinct datum tags: NAD 83(CORS96) for the CORS network's own active stations, and NAD 83(NSRS2007) for the passive (physically monumented) control marks tied to it. NGS's own 2011 FAQ reports the two realizations as very closely aligned — median differences on the order of 1 cm horizontally and 2 cm vertically — but acknowledges that the decision to use separate tags for what were, in practice, nearly coincident realizations caused persistent confusion among practitioners rather than clarifying the relationship between active and passive control.

2011: one tag, one multi-year solution

NAD 83(2011), epoch 2010.00, addressed that confusion directly by adopting a single datum tag for both active and passive realizations. Its active-station component, the Multi-Year CORS Solution (MYCS), reprocessed the full available CORS GPS observational history — January 1994 through April 2011, across 2,264 CORS and global stations — computing NAD 83 coordinates by transformation from the contemporary International Terrestrial Reference Frame realization (IGS08). Its passive-station component, the National Adjustment of 2011, then readjusted roughly 80,000 passive survey marks against this improved active-station solution.

Epistemic Notice

Most coordinates published in the NAD 83(NSRS2007) and NAD 83(2011) adjustments were not the product of new field observation campaigns at the passive marks themselves; rather, as an industry technical retrospective (*xyht*, 2017) notes, they were largely computed by readjusting existing GPS observations already on file, chiefly those collected during the earlier HARN/HPGN and Federal Base Network (FBN) campaigns of the 1990s and 2000s. A mark whose published coordinate has been updated through several successive NAD 83 realizations has therefore not necessarily been resurveyed at each step; this is reported here as a documented feature of how the national adjustments were actually computed, not as a criticism of their accuracy.

A patchwork of transformation tools, and why NATRF2022 does not extend it

Each realization boundary required its own transformation tool: NADCON bridged NAD 27 to NAD 83(1986) and, in later versions, to HARN/HPGN and FBN; GEOCON and its successor GEOCON2 were built specifically to carry coordinates from each state's post-1986 realization through NSRS2007 into NAD 83(2011) in a documented, consistent way. By the early 2010s this had produced, in the words of a 2024 industry technical review, "a patchwork of coverage at various epochs with no single-step solution," prompting NGS to begin

development of NADCON5 as a unified successor tool — the direct technical ancestor of the transformation apparatus this volume documents in Chapter 13 for the 2022 modernization itself.

Key Result

NAD 83(2011) is, and by design will remain, the last *realization to carry the NAD 83 name: the modernization this volume documents replaces the single national NAD 83 datum with four distinct, plate-fixed terrestrial reference frames (Chapter 2), each maintained through Euler-pole rotation (Chapter 3) rather than through a further periodic national readjustment of a single static network — a structural break with the 1986–2011 realization sequence summarized in this appendix, not merely its next increment.*

Epistemic Notice

This appendix's account of the 1986–2011 realization sequence is compiled from NGS conference and workshop presentation slides, an official NGS FAQ document, and industry technical retrospectives, rather than from the original NGS technical adjustment reports for each individual realization; figures such as the exact station counts and observation-window dates for the Multi-Year CORS Solution are reported as stated in these secondary NGS-affiliated sources, consistent with this volume's general sourcing practice for institutional and historical material of this kind.

Appendix D

Glossary of Acronyms and Technical Terms

Epistemic Notice

This glossary is a consolidation, not a new source of claims: every entry restates, in compressed form, a definition already given in the body of the volume, at the chapter cited in each entry. No entry introduces a fact, a figure, or a characterization that does not already appear there. Entries are ordered alphabetically by acronym or, where no acronym is in wide use, by the term itself.

AAGS / NSPS
: American Association for Geodetic Surveying / National Society of Professional Surveyors — the two professional associations cited, alongside FGCS, in connection with the regulatory and professional dimension of the transition (Chapter 25).

ATRF2014
: Australian Terrestrial Reference Frame, introduced in 2014 as the genuinely time-dependent, GNSS-native companion to the static GDA2020 — the reference point for the GDA2020/NATRF2022 structural comparison (Chapter 31).

CATRF2022
: Caribbean Terrestrial Reference Frame of 2022, one of the four plate-fixed frames replacing the single NAD 83 (Chapter 2).

CGVD2013(SGEOID2022)
: The Canadian vertical datum realization tied to the modernized geopotential model, corroborated by a Canadian Geodetic Survey conference paper (Chapter 28).

CGS
: Canadian Geodetic Survey, NGS's counterpart institution in the trilateral coordination with Canada and Mexico (Chapter 28).

CNMI
: Commonwealth of the Northern Mariana Islands, one of the U.S. insular areas served by MATRF2022 (Chapter 4).

CONUS
: Conterminous United States — the contiguous 48 states plus the District of Columbia, the primary territorial reference for NATRF2022 (Chapter 1).

CORS
: Continuously Operating Reference Station(s) — the GNSS station network underlying

the modernized system's paradigm shift from physical benchmarks to continuous electronic access (Chapter 15).

DFIRM
Digital Flood Insurance Rate Maps, FEMA's flood-hazard mapping products, whose vertical-datum dependency is discussed as a practical downstream impact of the transition (Chapter 27).

EGM2020 / GM2022
EGM2020 is the prior global gravitational-potential model; GM2022 is its NGS/NGA-developed update to degree and order 2190, one of the four components of NAPGD2022 (Chapter 7).

EPP2022
The Euler Plate rotation model used to remove the bulk rigid-plate-motion component from raw ITRF2020 velocities within each of the four frames (Chapters 2, 3, 33).

FCORS
Foundation CORS — the subset of CORS stations meeting the highest stability and monumentation standards (Chapter 15).

FEMA
Federal Emergency Management Agency, the federal body responsible for the DFIRM flood-map products discussed in connection with the transition (Chapter 27).

FGCS
Federal Geodetic Control Subcommittee, the interagency body whose approval vote formally governs adoption of the modernized system (Chapters 24, 25).

FGDC
Federal Geographic Data Committee, the coordinating body for the National Spatial Data Infrastructure under the Geospatial Data Act (Chapter 25).

GDA2020
Geocentric Datum of Australia 2020, the static, ITRF-aligned Australian reference frame used throughout the volume as the international precedent for a rigorous, continentally adjusted plate-fixed datum (Chapter 31).

GEMS
Geoid Monitoring Service, established by NGS in 2019 to track temporal changes in the geoid distinct from crustal motion (Chapter 10).

GEOID2022 / DEFLEC2022 / GRAV2022
The three gridded regional components of NAPGD2022 — geoid undulation, deflection of the vertical, and interpolated surface gravity, respectively — each split into static ("S") and dynamic ("D") parts (Chapter 7).

GIA Glacial isostatic adjustment — ongoing crustal deformation from the removal of Pleistocene ice loads, one of the geophysical drivers of geoid change tracked by GeMS (Chapters 10, 16).

GMSL
Global Mean Sea Level, distinguished in the volume from Local Mean Sea Level (LMSL) when discussing NAPGD2022's international context (Chapter 8).

GNSS
Global Navigation Satellite System(s) — the general term (encompassing GPS and other constellations) for the satellite positioning technology whose maturation made the NAVD 88 bias/tilt discovery possible (Chapter 1).

GRS 80
Geodetic Reference System 1980, the reference ellipsoid underlying NAD 83 and much of the volume's geodetic-height discussion (Chapters 1, 8).

HARN / HPGN
High Accuracy Reference Network / High Precision Geodetic Network — two names for the same GPS-based densification effort undertaken as part of NAD 83's history of realizations (Appendix C).

HTDP
Horizontal Time-Dependent Positioning, the legacy NGS program for shifting GNSS survey coordinates between epochs via a whole-crust geophysical model, superseded in the modernized system by the Intra-Frame Velocity Model (Chapter 16).

ICSM
Intergovernmental Committee on Surveying and Mapping, the Australian body overseeing the GDA2020 adjustment (Chapter 31).

IFDM2022 / IFVM
Intra-Frame Deformation Model / Intra-Frame Velocity Model — the modernized system's replacement for HTDP, providing epoch-to-epoch coordinate updates without requiring a causal explanation of the underlying motion (Chapters 16, 33).

IGS International GNSS Service, the international body coordinating GNSS station networks referenced in connection with Foundation CORS (Chapter 15).

IHRS
International Height Reference System, the global vertical-reference framework within which NAPGD2022 is positioned internationally (Chapter 8).

IERS
International Earth Rotation and Reference Systems Service, the body maintaining the ITRS/ITRF realizations (Chapter 5).

ITRF2020
International Terrestrial Reference Frame, 2020 realization — the global geocentric frame to which all four modernized North American frames are anchored (Chapter 5).

LCC / TM
Lambert Conformal Conic / Transverse Mercator — the two conformal projection families used for SPCS2022 zones, analyzed via Tissot's indicatrix (Chapter 21).

LDP / LDPZ
Low-Distortion Projection (Zone) — a locally optimized map projection zone, designed so that scale distortion stays within a stated tolerance (typically $\pm$ a few tens of ppm) across a limited area, the organizing design principle of SPCS2022 (Chapters 19, 21).

MATRF2022
Mariana Terrestrial Reference Frame of 2022, one of the four plate-fixed frames (Chapter 2).

NADCON / VERTCON
: The legacy horizontal and vertical coordinate-transformation tools bridging pre-modernization datum realizations, superseded by NCAT (Chapters 13, 30).

NAD 83
: North American Datum of 1983, the horizontal datum being replaced by the four modernized terrestrial reference frames (Chapter 1).

NAPGD2022
: North American–Pacific Geopotential Datum of 2022, the modernized vertical/geopotential datum replacing NAVD 88, built from the GM2022/GEOID2022/DEFLEC2022/GRAV2022 components (Chapter 7).

NATRF2022
: North American Terrestrial Reference Frame of 2022, the plate-fixed frame covering CONUS, most of Canada, and continental Alaska — the frame the volume treats as the default case (Chapter 2).

NAVD 88
: North American Vertical Datum of 1988, the vertical datum being replaced, found to be biased by roughly 50 cm and tilted by roughly 1 m across CONUS (Chapter 1).

NCAT
: NGS Coordinate Conversion and Transformation Tool, the unified successor to NADCON and VERTCON for the modernized system (Chapters 13, 30).

NCN
: NOAA CORS Network, the core federally maintained subset of the CORS network (Chapter 15).

NGA
: National Geospatial-Intelligence Agency, NGS's partner in developing the GM2022 gravitational model (Chapter 7).

NGDA / NSDI
: National Geospatial Data Asset / National Spatial Data Infrastructure — the data-governance categories defined under the Geospatial Data Act (Chapter 25).

NOAA / NGS
: National Oceanic and Atmospheric Administration / National Geodetic Survey — NGS, a line office of NOAA, is the federal agency responsible for the entire modernization described in this volume.

NSRS
: National Spatial Reference System, the overarching system — comprising the four terrestrial frames, NAPGD2022, and the supporting infrastructure — being replaced in its entirety rather than incrementally updated (Chapter 1).

OPUS
: Online Positioning User Service, the NGS tool allowing practitioners to submit raw GNSS observations for processing against the CORS network (Chapters 15, 32).

PATRF2022
: Pacific Terrestrial Reference Frame of 2022, one of the four plate-fixed frames (Chapter 2).

PLSS
: Public Land Survey System, the cadastral system whose monuments remain legally authoritative independent of the datum used to express their coordinates (Chapter 26).

REC / SEC
: Reference Epoch Coordinates / Survey Epoch Coordinates — the two coordinate types distinguishing a point's frame-fixed reference position from the coordinates of a specific GNSS observation at its own epoch (Chapter 12).

SGEOID2022 / SDEFLEC2022
: The static (epoch-2020.00) realizations of the GEOID2022 and DEFLEC2022 grids (Chapter 7).

SPCS / SPCS2022
: State Plane Coordinate System — the 1930s-origin state-level projection system, entirely redesigned for the modernized datum as SPCS2022 through direct state-by-state consultation with NGS (Chapter 19).

VDatum
: The NOAA tool for vertical-datum transformations among tidal, orthometric, and ellipsoidal height systems, paired with NCAT as the practitioner's transition toolkit (Chapter 30).

WGS 84
: World Geodetic System 1984, the geocentric reference frame used by GPS itself, distinct from but closely aligned with the ITRF family discussed throughout (Chapter 13).

Bibliography and Primary Sources

Epistemic Notice

All NGS sources listed were consulted directly (full document fetch, not merely via search engine) through July 2026. Industry and trade-press sources (Sanborn, xyHt, Trimble, GPS World, Geo Week News, The American Surveyor) are cited only for narrative context, or where explicitly flagged in place as the best available source short of a primary one (see the closing epistemic ledger below); no quantitative data derived exclusively from them has been reported as independently verified in the body of the text.

Classic physical-geodesy sources (Appendices A and B)

- Heiskanen, W. A., and Moritz, H., *Physical Geodesy*, W. H. Freeman, 1967 [standard reference textbook, cited in Appendices A and B via NGS Blueprint Part 2, Appendix B, for the classical Stokes-based treatment of the geoid and for the "one-meter approximation" historical benchmark].

- Hofmann-Wellenhof, B., and Moritz, H., *Physical Geodesy*, 2nd edition, Springer, 2006 [updated standard reference, cited alongside Heiskanen and Moritz 1967 for the modern treatment of spherical harmonic models, Bruns' formula, and Molodensky's theory].

- Kaula, W. M., *Theory of Satellite Geodesy*, Blaisdell, 1966 [source for the empirical degree-variance rule for geopotential coefficients cited in Appendix A].

- Vening Meinesz, F. A., *A formula expressing the deflection of the plumb-line in the gravity anomalies and some formulae for the gravity field and the gravity potential outside the geoid*, Proceedings Koninklijke Akademie van Wetenschappen te Amsterdam, 31, 1928 [source for the integral formula linking surface gravity anomalies to the deflection of the vertical, cited in Appendix A].

- Molodensky, M. S., Eremeev, V. F., and Yurkina, M. I., *Methods for Study of the External Gravitational Field and Figure of the Earth*, Israel Program for Scientific Translations, 1962 (translation of the 1960 Russian original) [primary source for the theory of normal heights and the quasigeoid cited in Appendices A and B].

- Snyder, J. P., *Map Projections: A Working Manual*, U.S. Geological Survey Professional Paper 1395, U.S. Government Printing Office, 1987 [standard reference for the closed-form Lambert Conformal Conic and Transverse Mercator scale-factor formulas derived in Chapter 21].

- Ghilani, C. D., *Adjustment Computations: Spatial Data Analysis*, 6th edition, Wiley, 2017 [standard geodetic-adjustment reference for the law of propagation of errors (variance-covariance propagation) applied to the fourteen-parameter transformation in Chapter 14].

- Segall, P., *Earthquake and Volcano Deformation*, Princeton University Press, 2010 [standard reference for the velocity-gradient-tensor decomposition into rigid rotation and strain rate, and for the principal-strain-rate and areal-dilatation-rate invariants, applied to IFDM2022 in Chapter 17].

Primary NGS/NOAA sources

- National Geodetic Survey, *Blueprint for the Modernized NSRS, Part 1: Geometric Coordinates and Terrestrial Reference Frames*, NOAA Technical Report NOS NGS 62, September 2017, revised 2021. `https://www.ngs.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0062.pdf` (accessed July 2026).

- National Geodetic Survey, *Blueprint for the Modernized NSRS, Part 2: Geopotential Coordinates and Geopotential Datum*, NOAA Technical Report NOS NGS 64, November 2017, revised February 2021. `https://www.ngs.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0064.pdf` (accessed July 2026).

- National Geodetic Survey, *New Datums Frequently Asked Questions (FAQs)*. `https://geodesy.noaa.gov/datums/newdatums/FAQNewDatums.shtml` (accessed July 2026).

- National Geodetic Survey, *Track Our Progress*. `https://geodesy.noaa.gov/datums/newdatums/TrackOurProgress.shtml` (accessed July 2026).

- National Geodetic Survey, *Release of the Modernized NSRS*. `https://www.ngs.noaa.gov/datums/newdatums/release.shtml` (accessed July 2026).

- Federal Register, *Updated Implementation Timeline for the Modernized National Spatial Reference System (NSRS)*, October 9, 2024. `https://www.federalregister.gov/documents/2024/10/09/2024-23347/` (accessed July 2026).

- National Geodetic Survey, *Blueprint for 2022, Part 3: Working in the Modernized NSRS*, NOAA Technical Report NOS NGS 67, 2019. `https://www.ngs.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0067.pdf`.

- National Geodetic Survey, *Learn More about SPCS2022*, Beta SPCS2022 site, last updated June 2025. `https://beta.ngs.noaa.gov/SPCS/learn-more.html` (accessed July 2026).

- Dennis, M. L., *The Future is Here: Introducing the State Plane Coordinate System of 2022*, paper presented at FIG Working Week 2023, Orlando, Florida. `https://repository.library.noaa.gov/view/noaa/56898/noaa_56898_DS1.pdf` (accessed July 2026).

- IGN/IERS ITRS Product Center, *Transformation parameters from ITRF2020 to past ITRFs*. `https://itrf.ign.fr/docs/solutions/itrf2020/Transfo-ITRF2020_TRFs.txt` (accessed July 2026).

- Gillins, D. T., Kerr, D., and Weaver, B., *Evaluation of the Online Positioning User Service for Processing Static GPS Surveys: OPUS-Projects, OPUS-S, OPUS-Net, and OPUS-RS*, *Journal of Surveying Engineering*, 145(3), 2019, American Society of Civil Engineers. `https://doi.org/10.1061/(ASCE)SU.1943-5428.0000280` (accessed July 2026).

- Galetzka, J., Sellars, I., Freeman, W., Coloma, F., Haw, D., Sun, L., and Saleh, J., *The NOAA CORS Network (NCN): A Brief History and Current Status*, National Geodetic Survey, 2023. `https://repository.library.noaa.gov/view/noaa/56914` (accessed July 2026).

- National Geodetic Survey, *NATRF2022, PATRF2022, CATRF2022, and MATRF2022*, Beta technical descriptions of the four 2022 terrestrial reference frames. `https://beta.ngs.noaa.gov/NATRF2022/` (accessed July 2026).

- National Geodetic Survey, *Procedures for Design and Modification of the State Plane Coordinate System of 2022*, policy document [source for the frame-to-territory zone assignments summarized in Chapter 4]. `https://www.ngs.noaa.gov/INFO/Policy/files/SPCS2022-Procedures.pdf` (accessed July 2026).

- Esri, *Prepare Your Data for the National Spatial Reference System Modernization of 2022 in the U.S.*, ArcGIS Blog, April 2026 [source for VERTCON 3.0 legacy vertical datum coverage by territory]. `https://www.esri.com/arcgis-blog/products/arcgis-pro/data-management/prepare-your-data-for-the-nsrs-2022` (accessed July 2026).

- Zilkoski, D. B., *NGS's first alpha products for the modernized NSRS*, *GPS World*, September 6, 2023 [source for the CONUS-wide ±159/±45 ppm SPCS 83/SPCS2022 design performance comparison, the ±50/±20 ppm NGS/stakeholder design-criterion split, and the Ohio (Columbus/COLB, Franklin LDP) and North Carolina (Monroe/NCMR) worked NCAT examples cited in Chapter 20]. `https://www.gpsworld.com/ngss-first-alpha-products-for-the-modernized-nsrs/` (accessed July 2026).

- Wisconsin State Cartographer's Office, *NGS Publishes SPCS2022 Parameters on Alpha Website*, *Wisconsin Geospatial News*, 2024 [source for the 59-LDP Wisconsin "WIGGS" layer and its parameter-table structure]. `https://www.sco.wisc.edu/2024/07/17/ngs-publishes-spcs2022-parameters-on-alpha-website` (accessed July 2026).

- Kentucky Division of Geographic Information, *The Kentucky State Plane Coordinate System Standards, Specifications, and Guidelines*, geodesy.ky.gov [source for the `KYLDP7NC-2022`/NGS 211007 KY NC zone designation and the six-step LDP design methodology]. `https://geodesy.ky.gov/assets/pdfs/KySPCS-SSD.pdf` (accessed July 2026).

- EPSG Geodetic Parameter Dataset, *SPCS83 Kentucky Single Zone (meter)*, EPSG:11630, and *NAD83 / Kentucky Single Zone*, EPSG:3088 [source for the legacy SPCS 83 Kentucky Single Zone defining parameters cited in Chapter 20 as a pre-2022 baseline only]. `https://epsg.io/11630`, `https://epsg.io/3088` (accessed July 2026).

- Utah Geospatial Resource Center / Utah.gov, *Creating New State Plane Zone for 2022*, blog post, 2018, updated 2024 [source for the Utah work group composition, the 15–25 zone design preference, and the 14-zone preliminary layout cited in Chapter 20]. `https://gis.utah.gov/creating-new-state-plane-zone-for-2022` (accessed July 2026).

- Zilkoski, D. B., *The effects of geoid changes in NGS's new, modernized 2022 NSRS*, *GPS World*, June 1, 2022 [source for the NOS NGS 69 GSFC mascon secular geoid rate maps over CONUS and Alaska, the 8 mm/5 yr xGEOID20 worked example, and the

Mount St. Helens elevation-change figures cited in Chapter 11]. https://www.gpsworld.com/the-effects-of-geoid-changes-in-ngss-new-modernized-2022-nsrs/ (accessed July 2026).

- National Geodetic Survey, *A Preliminary Investigation of the NGS's Geoid Monitoring Service (GeMS)*, NOAA Technical Report NOS NGS 69 [primary source, cited via Zilkoski above, for the CONUS/Alaska secular geoid rate maps]. https://geodesy.noaa.gov/library/pdfs/NOAA_TR_NOS_NGS_0069.pdf (accessed July 2026).

- National Geodetic Survey, *Progress of GEOID2022*, NGS Webinar Series presentation, 2022 [source for the published 1–2 cm/2–3 cm flat/mountain accuracy estimate and the GEOID2022 data inventory: xG20DEM, GOCO06S, GRAV-D, NGS/CGS/INEGI joint development, GDGF format]. https://geodesy.noaa.gov/web/science_edu/webinar_series/progress-of-geoid-2022.shtml (accessed July 2026).

- National Geodetic Survey, *GEOID2022 Alpha*, technical description [source for the 1-arcminute resolution, tide-free/GRS80/ITRF2020 reference, and static/dynamic component structure of the model]. https://alpha.ngs.noaa.gov/GEOID2022/ (accessed July 2026).

- The American Surveyor, *NGS Webinar: On the Trail of the Changing Alaskan Geoid: Results of the 2025 Geoid Monitoring Survey*, April 2026 [source for the fall-2025 southcentral Alaska GeMS follow-up campaign cited in Chapter 11]. https://amerisurv.com/2026/04/28/ngs-webinar-on-the-trail-of-the-changing-alaskan-geoid-results-of-the-2025-geoid-monitoring-survey/ (accessed July 2026).

- National Geodetic Survey, *2025 Recorded Webinars*, NGS Webinar Series [source for the 2024 Louisiana astronomical-camera geoid-slope validation survey with LSU, Oregon State University, and swisstopo, cited in Chapter 11]. https://www.ngs.noaa.gov/web/science_edu/webinar_series/2025-webinars.shtml (accessed July 2026).

- Zilkoski, D. B., *NGS presents the latest NSRS news at Geo Week 2026*, *GPS World*, March 3, 2026 [source for the updated FGCS vote timeline (late 2026/early 2027), the J. P. Blackwell Gravity Observatory renaming, the first-REC-iteration figures of more than 150,000 geometric and roughly 1 million geopotential coordinates, and the OPUS-S 5.2/OPUS 6.0/OPUS 6.1 development-phase details, all cited in Chapters 24, 12, and 15]. https://www.gpsworld.com/ngs-presents-the-latest-nsrs-news-at-geo-week-2026/ (accessed July 2026).

- National Geodetic Survey, *Key Milestones*, New Datums tracking page [source for the 120,000-mark geometric REC figure, the nearly 1,000,000-mark orthometric REC figure, and the MYCS3, GVX, LASER, SPROCCET, and GPS on Benchmarks software milestones cited in Chapters 12 and 15]. https://geodesy.noaa.gov/datums/newdatums/key-milestones.shtml (accessed July 2026).

- *xGGM23: an Updated Geoid Model for Mexico*, in International Association of Geodesy Symposia, Springer, 2026 [author names not resolved from the sources consulted; source for the GGM10/xGGM23 Mexican national geoid accuracy figures and their validation against the GSVS11/GSVS17 calibration lines, cited in Chapter 28]. https://link.springer.com/chapter/10.1007/1345_2026_366 (accessed July 2026).

Regulatory sources: the Geospatial Data Act

- U.S. Code, Title 43, Chapter 46 — *Geospatial Data* (Geospatial Data Act of 2018, Pub. L. 115–254, div. B, title VII, Subtitle F), 43 U.S.C. §§ 2801–2811. `https://uscode.house.gov/view.xhtml?path=/prelim@title43/chapter46&edition=prelim` (accessed July 2026).

- Federal Geographic Data Committee, *Geospatial Data Act of 2018*, official text and section-reference materials. `https://www.fgdc.gov/gda` (accessed July 2026).

- National Geodetic Survey, *New Datums Frequently Asked Questions (FAQs)* [cited again here for its explicit reading of GDA § 2809 as applied to NATRF2022/NAPGD2022 adoption]. `https://www.ngs.noaa.gov/datums/newdatums/FAQNewDatums.shtml` (accessed July 2026).

- U.S. Department of Health and Human Services, Office of Inspector General, *HHS Made Some Progress Toward Compliance With the Geospatial Data Act*, Report A-18-20-11500, 2020. `https://oig.hhs.gov/reports/all/2020/hhs-made-some-progress-toward-compliance-with-the-geospatial-data-act` (accessed July 2026).

- U.S. General Services Administration, Office of Inspector General, *GSA Is Not Fully Complying with the Geospatial Data Act*, Report A220037, and 2024 follow-up report A240028. `https://www.gsaig.gov/sites/default/files/audit-reports/A220037%20-%20Final%20Report%20-%20GSA%20Is%20Not%20Fully%20Complying%20with%20the%20Geospatial%20Data%20Act%20of%202018.pdf` (accessed July 2026).

- U.S. Department of Transportation, Office of Inspector General, *DOT Has Made Significant Progress Meeting the Requirements of the Geospatial Data Act of 2018 but Has Not Maintained an Accurate Inventory*, October 2024; and *Audit Initiated of DOT's Fiscal Year 2026 Compliance With the Geospatial Data Act of 2018*, February 2026. `https://www.oig.dot.gov/library-item/47126` (accessed July 2026).

- U.S. Department of Labor, Office of Inspector General, *DOL Continues to Make Progress Toward Compliance With the Geospatial Data Act of 2018*, Report 23-25-001-01-001, October 2024. `https://www.oig.dol.gov/public/reports/oa/2025/23-25-001-01-001.pdf` (accessed July 2026).

Quasi-primary and peer-reviewed sources on the Canadian side

- Donahue, B. et al., *Reference System Modernization in Canada*, Canadian Geodetic Survey / Natural Resources Canada, presentation at FIG Working Week 2023. `https://www.fig.net/resources/proceedings/fig_proceedings/fig2023/ppt/ts01g/TS01G_donahue_robin_et_al_12000_ppt.pdf` (accessed July 2026).

- Erickson, C., Banham, G., Berg, R., Chessie, J., Craymer, M., Donahue, B., Tardif, R., Thériault, Y., and Véronneau, M., *The U.S. is replacing NAD83 with NATRF2022: what this means for Canada*, *Geomatica*, 73(3): 74–80, 2019, Canadian Science Publishing. `https://cdnsciencepub.com/doi/10.1139/geomat-2019-0021` (accessed July 2026).

Sources on derived elevation products (3DEP / 3D Nation Study)

- U.S. Geological Survey, *2023 Lidar Partnership Awards Announced* [source for the 89% national 3DEP baseline coverage figure as of end of 2022]. `https://www.usgs.gov/news/technical-announcement/2023-lidar-partnership-awards-announced` (accessed July 2026).
- Congressional Research Service, *The 3D Elevation Program (3DEP) and Its Role in Mapping Hazards and Resources*, IF13079, August 2025. `https://www.congress.gov/crs-product/IF13079` (accessed July 2026).
- NOAA / USGS (Dewberry, contractor), *3D Nation Elevation Requirements and Benefits Study*, September 2022. `https://iocm.noaa.gov/reports/3dnationstudy/3D_Nation_Study_Final_Report.pdf` (accessed July 2026).
- U.S. Geological Survey, *Results Are In! 3D Nation Study Report Now Available*, technical announcement, 2022. `https://www.usgs.gov/news/technical-announcement/results-are-3d-nation-study-report-now-available` (accessed July 2026).
- U.S. Geological Survey, *3D National Topography Model*. `https://www.usgs.gov/3d-national-topography-model` (accessed July 2026).
- U.S. Geological Survey, *3DEP Broad Agency Announcement Frequently Asked Questions* [source for the 2026 baseline-completion estimate and the 3DNTM next-generation refresh strategy]. `https://www.usgs.gov/3d-elevation-program/3dep-broad-agency-announcement-frequently-asked-questions` (accessed July 2026).
- U.S. Geological Survey, *FY26 3DEP Data Collaboration Announcement (DCA)*. `https://www.usgs.gov/3d-national-topography-model/fy26-3dep-data-collaboration-announcement-dca` (accessed July 2026).

Sources on boundary law and surveying practice

- U.S. Bureau of Land Management, *Manual of Surveying Instructions for the Survey of the Public Lands of the United States*, 1973, U.S. Department of the Interior [primary source for the "unchangeable after passing of title" monument-control doctrine]. `https://archive.org/details/manualofinstruct00unit` (accessed July 2026).
- Robillard, W., Wilson, D., and Brown, C., *Boundary Control and Legal Principles*, 7th edition [standard boundary-law treatise, cited here via a conference paper summarizing the Land Act of 1805 and the unalterability of original PLSS corners]. `https://rowalaska.net/archives/projects/2015_collins_hall/research/Treatises/Simultaneous_Boundaries_From_Boundary_Control_and_Legal_Principles_7th.pdf` (accessed July 2026).
- PDH Academy, *Principles of Boundary Location*, continuing-education course materials [source for the *Rogers v. Taylor*, 45 S.W.2d 322 (Tex. App. 1932) case reference]. `https://pdhacademy.com/wp-content/uploads/2025/06/Principles_of_Boundary_Location.pdf` (accessed July 2026).
- Pallamary, M. J., *The Curt Brown Chronicles: Land Movements and Boundaries*, *The American Surveyor*, 2013 [source for the "original position of a monument... unalterable

except by reconveyance" formulation and the land-movement exception]. https://amerisurv.com/2013/09/28/the-curt-brown-chronicles-land-movements-and-boundaries/ (accessed July 2026).

- Smithson, T., *Rules of the Game: Coordinates as Boundary Evidence*, *xyHt*, 2017. https://www.xyht.com/professional-surveyor-archives/rules-of-the-game-coordinates-as-boundary-evidence/ (accessed July 2026).
- Mesabi Tribune (syndicated agricultural press), *GPS Changes in 2026 Could Affect Field Plans*, October 2025 [source for the illustrative RTK/auto-steer boundary-confusion case]. https://www.mesabitribune.com/around_the_web/news/gps-changes-in-2026-could-affect-field-plans/article_5cf6a948-6ed5-5b4c-aa7b-4eccfd62d61f.html (accessed July 2026).

Industry sources (narrative context, not verified data)

- Sanborn, *2025 Geospatial Industry Updates: NSRS Modernization*. https://sanborn.com/blog/2025-geospatial-industry-updates-nsrs-modernization/.
- xyHt, *Brave New Coordinates: What NSRS Modernization Means for Survey and GIS Practice*, March 2026. https://www.xyht.com/cartography-2/brave-new-coordinates-what-nsrs-modernization-means-for-survey-and-gis-practice/.
- Trimble Positioning Services, *NSRS and CSRS modernization*. https://positioningservices.trimble.com/en/nsrscsrs.
- GPS World, *A New Year's resolution for National Spatial Reference System users*, January 2026. https://www.gpsworld.com/a-new-years-resolution-for-national-spatial-reference-system-users/.
- GPS World, *NGS presents the latest NSRS news at Geo Week 2026*, March 2026 [source for the revised FGCS vote timeline, now anticipated late 2026/early 2027, cited in Chapter 13]. https://www.gpsworld.com/ngs-presents-the-latest-nsrs-news-at-geo-week-2026/.
- Geo Week News, *A Billion Points of Light*, March 2026 [source for the 3DEP baseline-completion announcement and the 76-trillion-lidar-point figure cited in Chapter 27]. https://www.geoweeknews.com/news/a-billion-points-of-light-3dep-usgs.
- Pallamary, C. ("Carl C."), *Bad Backsights: New Datum on the Horizon*, *The American Surveyor*, May 2026 [source for the trade-press readiness concerns regarding FEMA/D-FIRM and municipal budget constraints cited in Chapter 27]. https://amerisurv.com/2026/05/20/bad-backsights-new-datum-on-the-horizon/.

Sources on professional preparation, the US survey foot, and metadata practice

- Sanborn, *2025 Geospatial Industry Updates: NSRS Modernization* [cited again here for its COTS-vendor-readiness account (Esri ArcGIS, Autodesk, Global Mapper, TerraSolid) cited in Chapter 29]. https://sanborn.com/blog/2025-geospatial-industry-updates-nsrs-modernization/ (accessed July 2026).

- Martin, S. J., *The Deprecation of the US Survey Foot*, *The American Surveyor*, February 9, 2023 [primary trade-press source for the 85 FR 62698 Federal Register citation, the exact 1200/3937 m U.S. survey foot definition, the 2 ppm difference figure, and the 40-states-affected figure, cited in Chapter 29]. `https://amerisurv.com/2023/02/09/the-deprecation-of-the-us-survey-foot/` (accessed July 2026).

- Esri, *Change Is Afoot with the US Survey Foot*, *ArcNews*, Spring 2023 [source for Esri's confirmation that ArcGIS technology distinguishes the two foot definitions, and for the "one-eighth of an inch per mile" comparison, cited in Chapter 29]. `https://www.esri.com/about/newsroom/arcnews/change-is-afoot-with-the-us-survey-foot` (accessed July 2026).

- Wisconsin State Cartographer's Office, *A Final Farewell to the US Survey Foot?*, December 21, 2022 [corroborating source for the NIST deprecation notice, the 1893/1959/1986 unit history, and the metadata-diligence recommendation, cited in Chapter 29]. `https://www.sco.wisc.edu/2022/12/21/a-final-farewell-to-the-us-survey-foot/` (accessed July 2026).

- Cultivate Geospatial Solutions, *NSRS Modernization Is Here: What It Means for Survey, GIS, and Asset Management Teams* [source for the contract-language, procurement-specification, and QA/QC metadata-governance implications cited in Chapter 29]. `https://www.cultivategeospatial.com/nsrs-modernization-is-here-what-it-means-for-survey-gis-and-asset-management-teams/` (accessed July 2026).

- GoGeomatics, *Re-Centering Canada: Inside the Modernization of the Canadian Spatial Reference System*, September 25, 2025 [source, on the Canadian side, for Donahue's "not really possible without correct metadata" characterization of migration automation, cited in Chapter 29]. `https://gogeomatics.ca/re-centering-canada-inside-the-modernization-of-the-canadian-spatial-reference-system/` (accessed July 2026).

Sources on GDA2020 and the Australian modernization (international comparison)

- Dawson, J., and Woods, A., *Geocentric Datum of Australia 2020: the first Australian datum developed from a rigorous continental-scale adjustment*, *Journal of Spatial Science*, 2023 (open-access full article) [peer-reviewed primary source for the GDA2020 adjustment methodology, the ICSM Geodesy/Adjustment Working Group structure, the 6–11 cm ellipsoidal-height step, and the ICSM transformation-product suite, cited in Chapter 31]. `https://www.tandfonline.com/doi/full/10.1080/14498596.2023.2184429` (accessed July 2026).

- Spatial Source, *The new world of Earth-fixed datums*, May 8, 2017 [source for the 1.5–1.8 m regional shift range and the "dynamic datum is a misnomer" framing, cited in Chapter 31]. `https://www.spatialsource.com.au/new-world-earth-fixed-datums/` (accessed July 2026).

- NSW Spatial Services, *GDA2020*, and *GDA2020 Update Information Sheet*, June 2023 [state-government primary sources for the NSW-specific ∼1.5 m shift figure and the AGRS/ATRF rollout timeline, cited in Chapter 31]. `https://www.spatial.nsw.gov.au/surveying/geodesy/gda2020` (accessed July 2026).

- UNSW Newsroom / The Conversation, *Australia on the move: how GPS keeps up with a continent in constant motion*, 2017 [source for the Geoscience Australia ∼7 cm/year plate-motion figure and the two-stage (GDA2020/ATRF) modernization design, cited in Chapter 31]. `https://theconversation.com/australia-on-the-move-how-gps-keeps-up-with-a-continent-in-constant-motion-71883` (accessed July 2026).

- National Geodetic Survey, *Naming Convention*, New Datums technical page [cited again here for the explicit NATRF2022/PATRF2022/MATRF2022/CATRF2022 four-frame architecture, contrasted with Australia's single-plate case in Chapter 31]. `https://geodesy.noaa.gov/datums/newdatums/naming-convention.shtml` (accessed July 2026).

Sources on the Nebraska implementation case

- dymaptic, *Shifting to NATRF2022: Insights from a State Surveyor*, originally published April 2024, with a 2026 editorial update on the revised NGS timeline [sole source for the Nebraska State Surveyor (Casey C. Sherlock) interview material cited in Chapter 32: the county-then-region-then-state implementation sequencing, the NAD83(2011) baseline-alignment guidance, the OPUS Share submission practice, and the field-device international-foot configuration guidance]. `https://dymaptic.com/blog/shifting-to-natrf2022-insights-from-a-state-surveyor` (accessed July 2026).

Sources on uncertainty and error propagation

- National Geodetic Survey, *Progress of GEOID2022*, NGS Webinar Series [cited again here for the 1–2 cm/2–3 cm flat/mountain accuracy figures central to Chapter 33]. `https://geodesy.noaa.gov/web/science_edu/webinar_series/progress-of-geoid-2022.shtml` (accessed July 2026).

- ScienceDirect (Featherstone, Albayrak et al., cited via review), *Data requirements for the determination of a sub-centimetre geoid* [source for the external-accuracy/internal-error distinction in gravimetric geoid evaluation used to frame Chapter 33]. `https://www.sciencedirect.com/science/article/abs/pii/S0012825223000156` (accessed July 2026).

- Zilkoski, D. B., *OSU grant proposal includes developing time-dependent models for the new, modernized NSRS*, *GPS World*, February 8, 2024 [source for the IFDM2022/EPP2022 conceptual distinction, the Argentine ∼5 mm/2–3 cm stable/high-deformation precedent figures attributed to researcher "Demián," and the Houston-Galveston Subsidence District worked example, cited in Chapter 33]. `https://www.gpsworld.com/osu-grant-proposal-includes-developing-time-dependent-models-for-the-new-modernized-nsrs/` (accessed July 2026).

- Zilkoski, D. B., *Plate tectonics and NGS's new NSRS terrestrial reference frames*, *GPS World*, June 3, 2026 [source for the CORS COLA worked example — 14 mm/year ITRF2020 velocity and the resulting ∼0.3 ft June-2026 shift — cited in Chapter 33]. `https://www.gpsworld.com/plate-tectonics-and-ngss-new-nsrs-terrestrial-reference-frames/` (accessed July 2026).

Closing epistemic ledger: the state of the evidence as of July 2026

Epistemic Notice

The items below are not an action list for a future edition; this volume does not anticipate one. They are a permanent record of which specific claims, across the volume, rest on a fully corroborated primary source as of the consultation dates given above, and which rest on the best available quasi-primary or secondary source in the absence of one. Recording this distinction explicitly is itself part of the volume's argument (Chapter 25's closing section makes the point directly): a modernization observed while still taking shape necessarily yields a mixed evidentiary picture, and reporting that picture honestly is preferable to either withholding the still-open points or silently upgrading them to settled fact.

1. The numerical magnitude of the Eulerian rotations among the four reference frames (Ch. 2) rests on a verified single-station case (CORS COLA), corroborated by NGS's own Beta NATRF2022 site and a sector technical report.

2. Region-level quantitative shifts between NAD83(2011) and NATRF2022 (Ch. 23) rest on the NGS Beta SPCS2022 site (1–2 m, up to ~4 m) and an independent peer-reviewed Canadian estimate for the border region (1.3–1.5 m); no source consulted disaggregates these figures below the national/regional level cited.

3. The figure of 953 SPCS2022 zones (Ch. 19) is structurally corroborated by the NGS Beta SPCS2022 site as a NOAA/NGS-credited figure; this volume reports it at that level of corroboration, short of an independent recomputation from the underlying zone-definition table.

4. Canada's vertical-datum realization for the modernized frames (Ch. 28) is corroborated, as **CGVD2013(SGEOID2022)**, by a CGS-authored conference paper (Donahue et al., FIG 2023) — treated throughout this volume as a strong quasi-primary source, distinct from and short of a direct citation in Natural Resources Canada's own published documentation, which as of the sources consulted describes CSRS modernization only in general terms.

5. The 3DEP national baseline's completion (Ch. 27) is corroborated by USGS's own Geo Week 2026 announcement and its BAA/DCA documentation. The nationwide impact of the vertical datum transition on FEMA's DFIRM flood maps remains, as of the sources consulted, quantified nowhere beyond the 2010 North Carolina pilot study; a May 2026 trade-press column corroborates the underlying readiness concern qualitatively but supplies no figure. This volume reports the gap itself as a finding — the derived, third-party impacts of the transition remain comparatively under-documented relative to its geodetic core — rather than as a placeholder for a number this edition does not have.

6. The US survey foot's exact defining ratios and its December 2022 deprecation (Ch. 29) rest on a Federal Register citation (85 FR 62698) corroborated identically across five independent trade sources; no source consulted, however, provides a single authoritative cross-vendor COTS software readiness matrix, and this gap is reported as such rather than papered over.

7. The GDA2020/NATRF2022 structural comparison (Ch. 31) is this volume's own construction from independently sourced facts about each system (one peer-reviewed article, two Australian state/national government information sheets, one university newsroom account), not a comparison already published elsewhere and merely reported; no

institutional borrowing between the Australian and US design processes is claimed or implied.

8. Nebraska's county-then-region-then-state implementation sequencing (Ch. 32) rests on a single interview-format industry blog post, not on an NGS or Nebraska state-government primary source; it is reported at that single-source corroboration level throughout.

9. The IFDM2022/EPP2022 uncertainty figures (Ch. 33) — the centimeter-level target, the Argentine 5 mm/2–3 cm precedent, and the Houston-Galveston high-deformation illustration — rest on a single GPS World newsletter column quoting an NGS-affiliated researcher informally; no published NGS technical report with a formal IFDM2022 uncertainty budget was located among the sources consulted. The chapter's closing quadrature-combination synthesis of the geoid and deformation uncertainty terms is this volume's own construction, not a published NGS combination formula.

10. Chapters 21, 14, and 17 are, in a different sense from the rest of this ledger, self-contained: they derive standard closed-form cartographic and geodetic mathematics (Snyder's projection formulas, the classical law of covariance propagation, and the velocity-gradient/strain-rate decomposition, respectively) and apply it symbolically to structures already described qualitatively or partially elsewhere in this volume. They report no new empirical NGS figures and depend for their factual content only on the earlier chapters they extend (19–20, 13, and 3–16 respectively) plus standard, non-controversial textbook mathematics; no numerical NGS-published covariance matrix for EPP2022/IFDM2022, nor an NGS-published tensor-form treatment of IFDM2022, was located among the sources consulted, and neither chapter claims one.